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Peer Review File

Enhanced structural diversity increases European forest resilience and may compensate climate-driven declines

Corresponding Author: Dr Mark Pickering

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

Version 0:

Decision Letter:

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Dear Dr Pickering,

Your manuscript titled "Enhanced structural diversity increases forest resilience and may compensate climate-driven declines" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point 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.

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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still 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.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Mengjie Wang
Associate Editor
Communications Earth & Environment
@CommsEarth

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The article explores a classic ecological question: how does trait diversity contribute to forest resilience? The authors use high-resolution remote sensing datasets and multiple analytical methods, e.g., Random Forest and Partial Dependence analysis, to examine this relationship. Their findings highlight the importance of two canopy diversity indices (FSDV and FSDH+V) in predicting resilience. The study is well-structured and highly insightful. I have a few suggestions and questions for the authors:

Major Comments:

1. line257-268. The data presented here can not be easily drawn from Figure 5c. If the goal is to illustrate how "the strength of the resilience–FSD relationship varies as a function of temperature," I recommend plotting a new figure where the x-axis represents FSD, the y-axis represents resilience, and different colored lines indicate different temperature levels.
2. In Figure H9, FSDH and FSDH+V show a significant positive correlation, whereas FSDV and FSDH+V exhibit a non-significant negative correlation. However, in the Random Forest results (Figure B3), FSDH ranks lower in predictor importance compared to FSDV and FSDH+V, which seems counterintuitive. Please verify these results. Additionally, consider training the Random Forest model with all three FSD indices together to check if their relative importance rankings change.
3. In the method section, the explanation of these FSD indices is difficult to understand. For example, what does Xi represent in the FSDV equation, and what is its corresponding metric in the GEDI dataset? I suggest providing a visual representation of the data processing method using a illustrative figure.

Minor Comments:
- Replace all instances of "machine learning" with "Random Forest" for greater specificity.
- Modify the title to "European Forest" instead of just "Forest" for accuracy.
- In Figure H9, clarify the meaning of "TAC" in the Methods section.
- In Figure E7, confirm whether it truly represents a plot of isolines.

Reviewer #2 (Remarks to the Author):

Overall，the manuscript tackles an important and timely topic by linking forest structural diversity—quantified through multiple remote sensed metrics—with ecosystem resilience under climate change pressures. The integration of high-resolution GEDI data with MODIS kNDVI time series and ERA5-Land climate products, combined with a robust Random Forest modeling framework, represents a significant advance in understanding the spatial variability of forest recovery dynamics and its linkage with structure diversity. The discussion relating these findings to forest management practices is also insightful and policy relevant.

Here I have some moderate suggestions to improve this study. First, the manuscript presents a comprehensive and technically sophisticated methodology, particularly in the derivation of the resilience metrics (AC1- and variance-based restoration rates) and the use of partial dependence and ICE analyses. However, further discussion on the uncertainty associated with key parameters (e.g., the choice of the GEDI-based FSD metrics and the parameters within the Random Forest model) would strengthen the conclusions. In particular, quantifying the uncertainty in remote-sensing inputs and discussing its potential propagation through the modeling framework could enhance the robustness of the interpretations. Second, one of the key conclusion of this study is more importance by vertical structural diversity than horizontal structural diversity in contributing to resilience. Estimate of horizontal structural diversity vs vertical structural diversity may depend on the spatial scale. In particular, the horizontal structural diversity could be relatively high in drier regions which would depend on spatial scale. Thus, I am curious whether and how the spatial scale of data analysis could influence the results across rainfall gradient. Third, resilience is a concept with temporal response to disturbance. This study examined the spatial relationship between resilience and structural diversity and other climate variables. In figure 5 and section ‘under climate warming’, I am curious whether the rate of climate warming instead of 2m temp mean could be used. Moreover, N deposition seems to be an important variable as well.

I also have the following very minor suggestions to improve this study

Figures: may consider adding a compass and latitude and longitude to each map
Line 53: could delete ‘through’
Lines 83-92: some more details on how the AC1 is estimated would be useful, i.e., in term of spatial and temporal scales and in response to what types of disturbance.
Line 129-132: this difference may be related to rainfall gradient with potential higher horizontal diversity in drier regions.
Section on random forest models: may consider having linear analysis as well with explicitly accounting for interaction of structural diversity with climate (i.e., temperature/warming).
Line261：use“offset” instead of “compensate for”
Discussion: may discuss a bit about the caution of using AC1 and/or variance as indicators of resilience. Previous studies have showed lack of early warning signals with regime shift, i.e., by rate induced tipping (Huang et al., 2024) and also variance as a better predictor for stochastically driven abrupt transition (Chen et al., 2018).
Line621：the sentence“The Random Forest uses 500 trees and 7 variables sampled at each split, chosen via a 10-fold cross-validation optimization process.” could be refreshed as “The Random Forest model comprises 500 trees, with 7 variables sampled at each split, as determined by a 10-fold cross-validation optimization process.”

References
Huang et al. 2024. Deep learning for predicting rate-induced tipping
Chen et al., 2018. Rising Variability, Not Slowing Down, as a Leading Indicator of a Stochastically Driven Abrupt Transition in a Dryland Ecosystem

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Version 1:

Decision Letter:

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Dear Dr Pickering,

Your manuscript titled "Enhanced structural diversity increases European forest resilience and may compensate climate-driven declines" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

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

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

Best regards,

Mengjie Wang

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

satisfied with the revise

Reviewer #2 (Remarks to the Author):

The revised manuscript has largely addressed my previous suggestions in term of robustness of results, spatial scale et al. I am also highly impressive by the findings with insightful discussions of this interesting study. It is good to learn that diversity in canopy complexity is a better predictor of resilience than spatial variability in canopy height.

Here I only have minor suggestions for the authors to consider.

Abstract lines 24-29: if possible, may consider simplifying the presentation of methods which would save the number of words if there is word limit in abstract.

Lines 45-46: this sentence could be improved, i.e., 'decline of forest resilience under increasing global change and disturbances with rising tree mortality…'

Lines 51-52: perhaps 'as natural systems approach bifurcation points' could be rephrased to 'to detect the bifurcation points of natural systems'

Lines 290-292: may consider suggesting that this pattern may be different in dryland forests

Line 327: could add 'that' before 'alternative'

We thank the reviewers for their constructive comments and suggestions. We aim to take them fully into account in our revised manuscript, highlighted for differences. Please note that there are some sections highlighted in the new manuscript that are not necessarily different in content from the previous version but they are highlighted for mild formatting reasons such as a change pushing an unrelated word/paragraph to the next page. Below, please find in-line our responses.

Reviewer #1

The article explores a classic ecological question: how does trait diversity contribute to forest resilience? The authors use high-resolution remote sensing datasets and multiple analytical methods, e.g., Random Forest and Partial Dependence analysis, to examine this relationship. Their findings highlight the importance of two canopy diversity indices (FSDV and FSDH+V) in predicting resilience. The study is well-structured and highly insightful. I have a few suggestions and questions for the authors:

1. line257-268. The data presented here can not be easily drawn from Figure 5c. If the goal is to illustrate how "the strength of the resilience–FSD relationship varies as a function of temperature," I recommend plotting a new figure where the x-axis represents FSD, the y-axis represents resilience, and different colored lines indicate different temperature levels.

Thanks for the suggestion. In Figure 5c, we show isolines of the AC1-derived resilience corresponding to the median conditions of each BGR (biogeographical region) across a range of temperature and combined diversity values around the median values of the BGR. The lines represent the isolines of AC1-derived resilience (extracted at the median conditions of the BGR) in a 2d pdp (combined diversity and temperature). This display was chosen as it enabled us to demonstrate how the resilience-diversity relationship might change under a range of temperature increases. The approach explores the climate domain of 2d partial plot in a third temperature dimension. We take on board the reviewers suggestion and we have reproduced the figure, in order to better convey the intended message. This alternative approach explores the spatial domain of an averaged 1-dimensional partial dependence plot and then boosts the dataset by 1C and creates a second 1d pdp. As the methodology is different, we can expect similar general trends, but with likely with slightly different numbers (on top of the fact that there have been some other changes to the analysis e.g. addition of input variables and changes in the uncertainty calculation\, see the rest of the review responses).

In the new Figure 5c (below), the x-axis represents the combined FSDH+V and the y-axis the AC1-derived resilience (we also update the appendix figures). For each BGR (biogeographic region), the 1d pdp of the AC1-derived resilience on the combined FSDH+V is shown for both the current temperature values (solid lines) and for the temperature values increased to 1 ◦C (dotted lines).

The horizontal dotted lines represent the AC1-derived resilience values modelled at the current median diversity condition of each BGR. We agree with the reviewer that the new figure more directly displays the fact that - in order to maintain the AC1-derived resilience corresponding to the current median diversity condition of the BGR - the diversity must increase under the elevated temperature conditions. The partial dependence plot of the higher temperature increase is also outside the 95% confidence interval of the current temperature partial dependence plot.

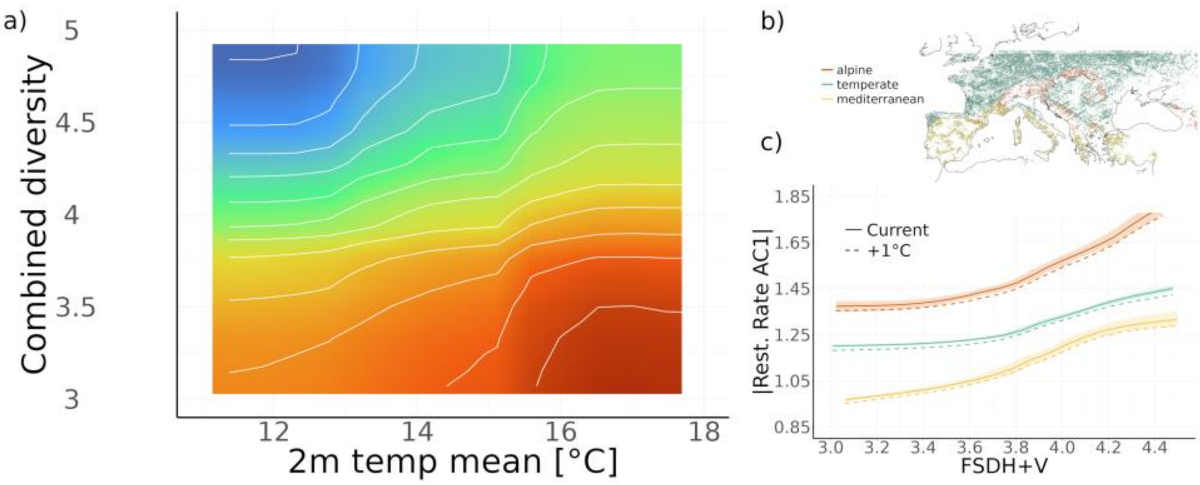


Fig. 5 The interplay between forest resilience, structural diversity and temperature. (a) Two-dimensional partial dependence plot of the AC1-derived restoration rate of Central and Southern European forests as a function of the mean background temperature and the combined horizontal and vertical structural diversity (FSDH+V) metric. (b) Distribution of the separate biogeographical regions considered in the analysis. (c) Partial dependence of the AC1-derived restoration rate on the FSDH+V metric for the three different biogeographical regions of European forests. Two different mean background temperature scenarios are shown, the 2003-2019 mean (line) and a 1°C increase on this (dashed). A bootstrapping process is used to derive bands displaying the model and FSD metric uncertainty. The figures for the alternative resilience and diversity metrics can be found in extended data F.

As with the previous Figure 5c, the required increase in combined FSD can be quantified (though less precisely, since the 1d pdp might not retain exactly the value corresponding to the median combined FSDH+V of the BGR). In the near-term, in order to compensate for a warming of 1◦C the FSDH+V metric would need to shift from the current median region value to values 0.054 (0.018-0.107), 0.082 (0.041-0.123), and 0.120 (0.040-0.200) higher for the respective alpine, temperate and Mediterranean regions (95% confidence interval in brackets). These higher values of FSDH+V are currently found at approximately the 55th, 57th and 60th respective percentiles of the regional FSDH+V distributions. Compensating 1◦C of warming therefore, specifically, requires respective 4.8% (1.5-9.4%), 7.1% (3.6-10.6%) and 10.2% (3.2-17.4%) increases in the median combined FSDH+V diversity (95% confidence interval in brackets), relative to the current observed alpine, *temperate and Mediterranean regional diversity distribution. For the variance-derived restoration rate, the equivalent values are: 4.8% (1.5-9.4%), 5.3% (0.1-8.8%) and 17.4% (8.3-23.4%)*

Even though the same overall trend can be observed as compared to the old Figure 5c, different values are found and a different ordering of BGR importance. This is likely due to slight changes in the positions of the estimated median BGR values in 2d vs 1d partial dependence space, as well as the changes to the random forest model mentioned previously.

Due to the change in order of importance of the BGRs, we propose to drop the paragraph starting L272, ('A smaller increase in the FSD is therefore required to compensate temperature rises in the Mediterranean and alpine regions, compared to the temperate region.') as it is clear that slight changes in the parameters of the temperature increase projection can vary the order of sensitivity between BGRs. whilst this paragraph was previously highly speculative - it is probably better not to say which BGR is more reactive at all, particularly given the large and overlapping confidence intervals.

Throughout the manuscript (abstract, results discussion) we change the text to reflect the new values. We also change the text describing the figure to reflect these changes from L251:

'The same 2d-space of temperature and FSD can be built with points added to represent the median daily temperature and median value of the combined FSDH+V metric for three biogeographical groupings of European forests: alpine, temperate (including continental areas) and Mediterranean (figure 5b & c). Incremental changes up to 2.5◦ C are added to the region's modelled median daily temperature to simulate the short-term temperature rises associated with global warming. In order to maintain simplicity, non-temperature changes associated with global warming, such as increased variability of precipitation, are not considered.'

to:

The partial dependence of the AC1-derived restoration rate on forest structural diversity shown in figure 3, can be reproduced with lines separately representing three biogeographical groupings of European forests: alpine, temperate (including continental areas) and Mediterranean (figure 5b and 5c). An incremental change of 1◦ C is also added to each pixel's mean daily temperature to simulate the short-term temperature rises associated with global warming, and the resulting resilience-FSD dependence shown. In order to maintain simplicity, non-temperature changes associated with global warming, such as increased variability of precipitation, are not considered.

Figure 5c can be interpreted in terms of the change required by the model in the combined FSDH+V metric in order to compensate increases in the regional temperature and maintain the current observed levels of resilience. In each region, as average temperatures rise, resilience is maintained when FSDH+V increases beyond the 95% confidence interval. In the near-term, in order to offset a warming of 1° C the metric would need to shift from the current FSDH+V median regional value to values 0.054 (0.018-0.107), 0.082 (0.041-0.123), and 0.120 (0.040-0.200) higher for the respective alpine, temperate and Mediterranean regions (95% confidence interval in brackets). Expressed in terms of the changes in the diversity metric relative to the distribution in each biogeographical region, offsetting 1° C of warming requires respective 4.8% (1.5-9.4%), 7.1% (3.6-10.6%) and 10.2% (3.2-17.4%) increases in the median combined FSDH+V diversity, relative to the current observed alpine, temperate and Mediterranean regional median diversity. For the variance-derived restoration rate (extended data F10) the corresponding relative increases are, respectively, 4.8% (1.5-9.4%), 5.3% (0.1-8.8%) and 17.4% (8.3-23.4%) It should be noted that the scaling in all models is non-linear, and the exercise pushes the models towards areas of sparse training data where it is less stable. However, for the purposes of projecting climate warming in the short-term, the data coverage is reliable.

2. In Figure H9, FSDH and FSDH+V show a significant positive correlation, whereas FSDV and FSDH+V exhibit a non-significant negative correlation. However, in the Random Forest results (Figure B3), FSDH ranks lower in predictor importance compared to FSDV and FSDH+V, which seems counterintuitive. Please verify these results. Additionally, consider training the Random Forest model with all three FSD indices together to check if their relative importance rankings change.

Regarding the negative correlation this is a very good observation, that essentially is due to us forgetting to update the code for this figure following a mid-analysis change in definition of FSDV (previously referred to as 'vertical diversity') as well as redefining the restoration rates as 'absolute restoration rates'.

In an early version of the analysis, we were analysing 'vertical structural diversity' as the excess kurtosis (such that when there is negative kurtosis - referred to as platykurtic - there is less vegetation in the distribution tails https://www.scribbr.com/statistics/kurtosis/). This however meant that for the 'vertical diversity' metric, the more negative value was associated with higher diversity, whilst for the other diversity metrics the higher the metric, the higher the diversity. As such the vertical diversity metric - resilience relationship was also inverted compared to the other structural diversity metrics. Figure H9 shows this definition: vertical diversity is anti-correlated with 'horizontal diversity' and with 'combined diversity'. So in figure H9 the correlation between vertical vs horizontal/combined metrics is consistent with vertical diversity metric vs Rest. Rate, and with the concept: a more negative 'vertical diversity metric' is associated with more vertical diversity.

In order to make the paper easier to follow for the reader, we chose to define the FSDV metric as the inverse excess kurtosis (see the negative symbol in eq. 5, section Methods: Forest Structural Diversity Metrics) i.e. FSDV = (- 1) x the previous 'vertical diversity' metric. This means that across all the FSD metrics, higher value are associated with greater forest structural diversity. It also means that for each metric the FSD-resilience relationship is consistently positive (i.e. more FSD is associated with more structural diversity and is associated with higher Rest. Rate).

In the code (see the various plotting scripts of the github, with the exception of the plot_dataframe_correlationMatrix.R) this late-decided 'hack' - inverting the excess kurtosis (referred to as mu_kurt in the code) to create the 'FSDV' metric - can be seen in the following lines:

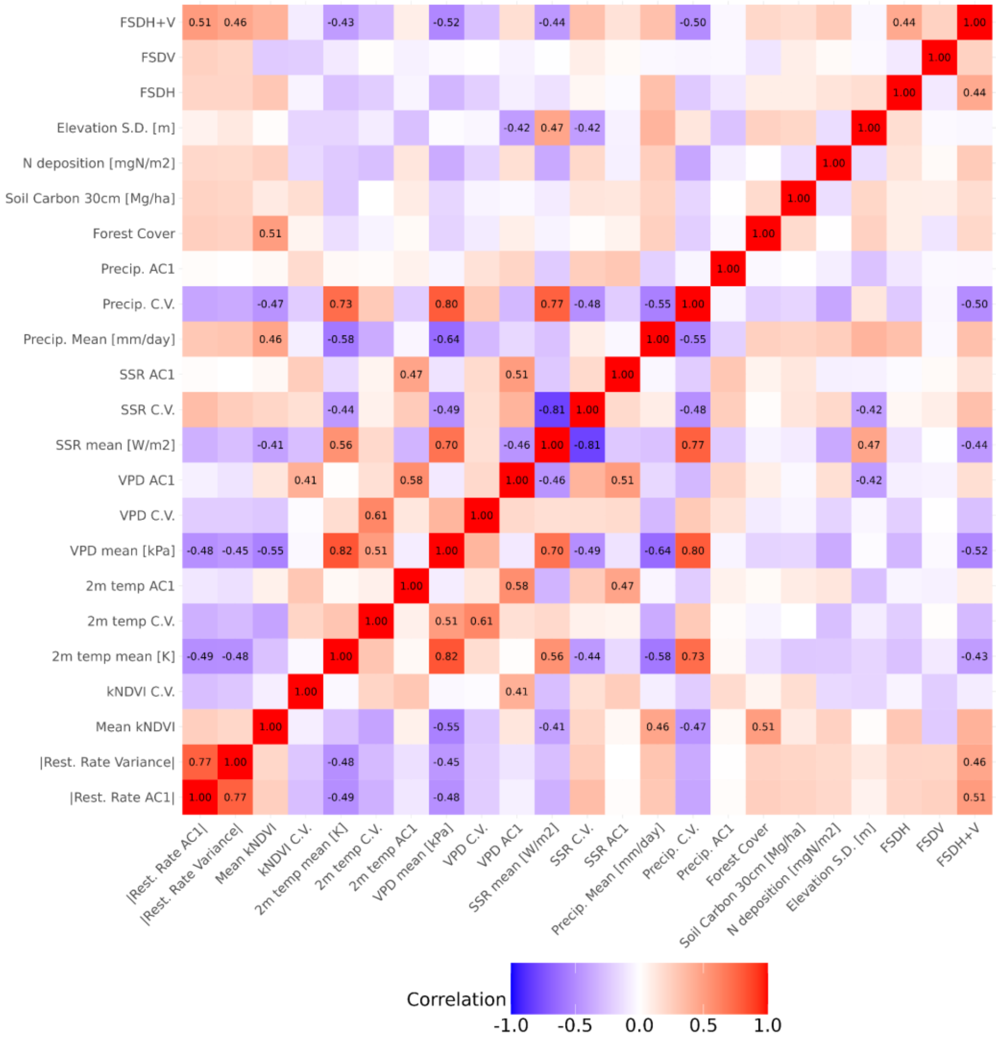
```
# invert diversity metrics?
if(b_invert_mu_kurt & col_name== 'mu_kurt'){
df_comb_var[col_name] <- -1 * df_comb_var[col_name]
var_unit <- paste0(var_unit, '_inv')
```

```
print('invert mu_kurt') }
```

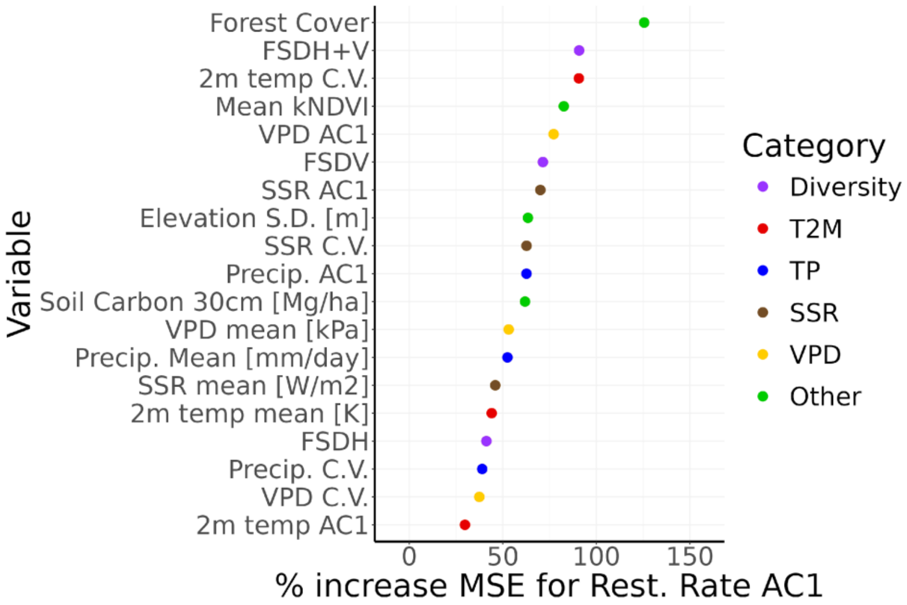
However, we simply forgot to update this for the correlation matrix (a figure produced early on in the analysis). This lack of update is also reflected in the fact that we use the previous nomenclature of the FSD metrics (vertical diversity, horizontal diversity, combined diversity) where the other figures use the updated 'FSD' format names. H9 also includes a previously considered resilience metric 'kNDVI TAC' which is not used in the paper (TAC refers to the temporal autocorrelation - often called AC1 - which we do not use in this form in our paper, instead focussing on the more reader-interpretable restoration rates – one of which is derived from the AC1).

In order to correct this oversight, we added the lines of code above (inverting the excess kurtosis or 'vertical diversity metric' into the 'FSDV metric' consistent with the rest of the paper). This switches the direction of the correlation for the vertical diversity metric, aligning the correlation map with the results of the rest of the paper i.e. positive relationship between FSD-|Rest. Rate| and a slight (0.24) positive correlation between FSDV and FSDH+V. There is a slight, insignificant negative correlation of -0.09 between FSDV and FSDH (i.e. the separate vertical and horizontal metrics are not strongly correlated). Re-running the figure production code also updated the FSD metric names and removed the kNDVI TAC (this parameter - although present in the dataset and the code, and used to calculate the AC1-derived Rest. Rate - is not referenced elsewhere in the document). The new figure can be found in the updated manuscript as supplementary material figure H9. We believe this resolves the issue.

Additionally, in this late update to the metrics the 'Restoration Rates' – in the literature often defined such that they have a negative sign (ie restore displacements in the direction of equilibrium) – were re-defined as absolute restoration rates in this paper. This similarly was designed with the intention to make the reading easier (a larger positive value = more resilience). However this was not updated in the previous correlation table, H9. We have now updated the code and figure to reflect this '| Restoration Rate |' definition. As such the restoration rates have positive `correlations with the FSD metrics (as expected from the partial dependence figures). Using an older version of definitions in Figure H9 was a large oversight, and we thank the reviewer for this important update. Finally we also include the nitrogen deposition metric discussed elsewhere.



On the second point, we did not originally train the RF with all three diversity metrics as inputs as they have some correlation (as expected and shown in H9), and so this would likely result in some of the 'importance' and 'FSD-Rest.Rate relationship' being 'spread' across the three FSD metrics, ultimately making the interpretation of results more complex. However, we have re-run the model with all three FSD metrics present, and below you can see the variable importance rankings.



The findings are consistent with the results expected from figures 2b and supplementary figures B3. FSDH+V is the most important of the diversity metrics (as measured through relative increase in MSE), followed by FSDV, and with FSDH among the lower ranked metrics. For each FSD metric, both the ranking and the relative increase in MSE drops slightly, likely due to their colinearity and therefore 'sharing' some of the model contribution with the other structural diversity metrics. The other (environmental) variables included in the study have a % increase in MSE within the uncertainty bounds shown in the previous figures (and therefore do not significantly change). The FSDH being lower ranked than FSDV despite being more strongly correlated with FSDH+V, the strongest predictor, is not an issue as this suggests that there are non-linear factors at play, which the RF model is accounting for (but not the correlation).

Please note that we have only run these multi-FSD results for the AC1-derived restoration rate (rather than the variance derived rate) and we have not run the 100 bootstrapped versions for a corresponding model uncertainty estimate, however we do not expect the findings to change significantly. As this figure is to check the order of importance of the diversity metrics do not include this additional result in the paper or supplementary information (however we would be happy to include them, if you wish).

3. In the method section, the explanation of these FSD indices is difficult to understand. For example, what does Xi represent in the FSDV equation, and what is its corresponding metric in the GEDI dataset? I suggest providing a visual representation of the data processing method using a illustrative figure.

Thanks for this useful point, we are happy to clarify and will improve the explanation in the text. The Xi here refers to the vertical distribution of the return energy of the GEDI lidar shots, i.e. the *reflectance energy (reflected by e.g. leaves, branches, etc) distribution of the laser in the vegetation vertical profile (see figure 3. https://www.sciencedirect.com/science/article/pii/S2666017220300018).*

Elsewhere in the text we refer to this reflectance energy distribution in the vertical profile as 'RH' (the relative heights of the return energy) (L497):
'The derived metrics include … forest Relative Height (RH) percentiles of the Vertical Profile (VP) of vegetation distribution. RH98, for example, represents the forest height at which 98% of the reflected GEDI light is returned, relative to the ground,'

We improve this text adding specific reference to figure 3. of the aforementioned GEDI paper such that this line is adjusted to: '… forest Relative Height (RH) percentiles of the Vertical Profile (VP) of vegetation distribution (see Figure 3. Ref [38]).'.

We perform the excess kurtosis calculation on these RH values (i.e. on the vertical distribution of laser return energy to the GEDI satellite), and there is therefore no reason to create a new variable Xi (RH serves as both specific heights, e.g. RH98, as well as the full return energy distribution, RH). We have updated the text for the formula (5), replace X_i with RH_i and clarify the terms in L516:

The vertical structural diversity, FSDV ($-\tau_{KU}$ in Ref. [39]), is defined as the inverse of the mean excess kurtosis in the pixel:

$$\mathrm{FSDV} = -\frac{1}{N}\sum_{i}^{N}\left(\frac{\mathbb{E}[(RH_i - \mu(RH_i))^4]}{(\mathbb{E}[(RH_i - \mu(RH_i))^2])^2} - 3\right) \tag{5}$$

where RH_i is the above ground Relative Height return energy distribution within the i^th GEDI sample shot, across a pixel with N GEDI samples. FSDV is a good

This definition is also now consistent with the other metric definitions (e.g. FSDH based on RH98_i).

Minor Comments:

- Replace all instances of "machine learning" with "Random Forest" for greater specificity.

> Done

- Modify the title to "European Forest" instead of just "Forest" for accuracy.

> Done, we were slightly concerned about the title length, but it is now: 'Enhanced structural diversity increases European forest resilience and may compensate climate-driven declines'

- In Figure H9, clarify the meaning of "TAC" in the Methods section.

> This is addressed in the major comment above. It is an oversight as this figure was made when we were also analysing the temporal autocorrelation (which we initially called TAC, and later

switched to the more standard 'AC1') itself. In the paper we only look at the restoration rates (which incorporate TAC). Reproducing/updating the figure automatically removed the label 'TAC' from the figure.

- In Figure E7, confirm whether it truly represents a plot of isolines.

We can confirm that the plot represents the isolines of constant resilience as a function of temperature and FSD. This is confirmed not just by rechecking and rerunning the code, but the pattern fits the alternative formulation of the figure suggested in the first comment from the reviewer (See response to Q1). Please let us know if we can provide further clarity.

Reviewer #2

Overall, the manuscript tackles an important and timely topic by linking forest structural diversity—quantified through multiple remote sensed metrics—with ecosystem resilience under climate change pressures. The integration of high-resolution GEDI data with MODIS kNDVI time series and ERA5-Land climate products, combined with a robust Random Forest modeling framework, represents a significant advance in understanding the spatial variability of forest recovery dynamics and its linkage with structure diversity. The discussion relating these findings to forest management practices is also insightful and policy relevant.

Here I have some moderate suggestions to improve this study:

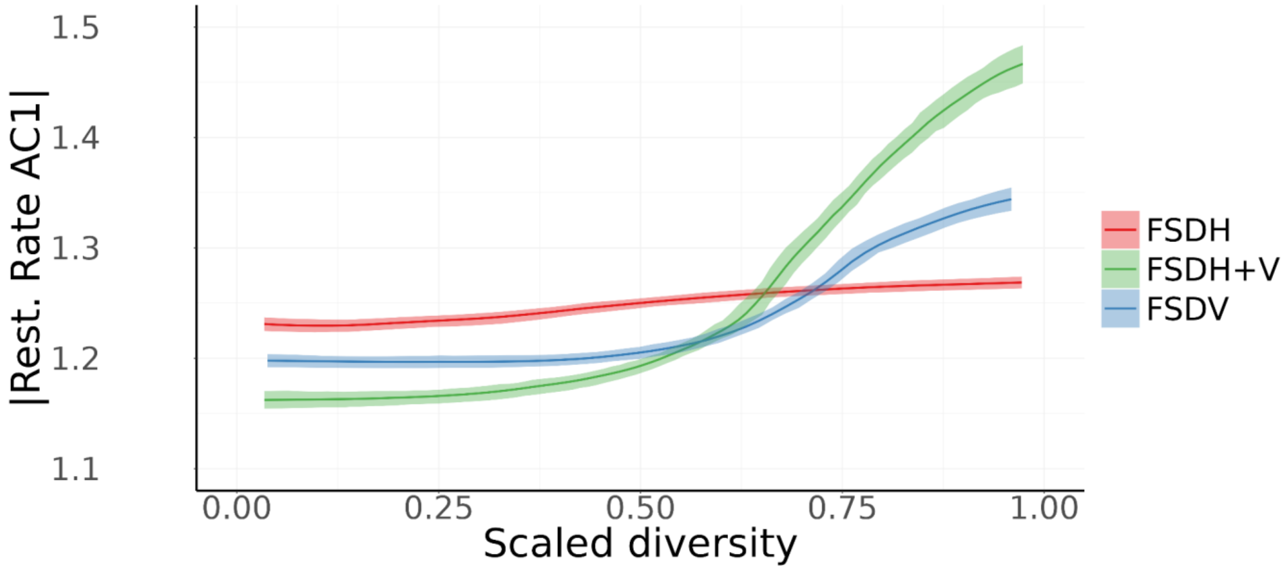
First, the manuscript presents a comprehensive and technically sophisticated methodology, particularly in the derivation of the resilience metrics (AC1- and variance-based restoration rates) and the use of partial dependence and ICE analyses. However, further discussion on the uncertainty associated with key parameters (e.g., the choice of the GEDI-based FSD metrics and the parameters within the Random Forest model) would strengthen the conclusions. In particular, quantifying the uncertainty in remote-sensing inputs and discussing its potential propagation through the modeling framework could enhance the robustness of the interpretations.

Thank you for this comment which will improve the robustness of the work. As suggested, we have quantified the uncertainty in the remote sensing inputs to the RF model. Please note that some of the results and figures elsewhere in the analysis will have changed to reflect this.

For the uncertainty on the standard deviation in the 98th percentile of the relative heights, we use the standard error formula of $SE(\sigma) = \sigma / \sqrt{2N - 2}$. For the other two forest structural diversity metrics we use a bootstrapping approach to estimate the uncertainty. We rerun the calculation of the GEDI-based FSD metrics with a 100 times bootstrapped (with-replacement) resampling in order to calculate the variability of each pixel's excess kurtosis (FSDV) and shannon entropy (FSDH+V). We take the standard deviation as the uncertainty on each metric, and, along with the standard error on the standard deviation in RH98, we propagate the uncertainties through the analysis in order to get more accurate uncertainty bounds on the relationship.

The propagation through the analysis is done for each metric by bootstrapping 100 RF models for the model uncertainty (as completed previously) whilst adding an addition recalculation of the FSD metric in each model by selection each pixel's FSD metric value from a normal distribution with mean as the originally calculated (mean) FSD metric value, and standard deviation as the new FSD uncertainty. We therefore assume normality in the FSD metric distribution.

The figures and findings are updated to reflect the new uncertainties associated with the remote sensing inputs (the FSD metrics). For example below the updated 'Fig. 3 The relationship between European forest resilience and structural diversity' and the corresponding caption updated.



The 'Forest structural diversity metric' section of the methodology is updated to explain how the uncertainties are calculated L525:
'Uncertainty in FSDH estimated using the standard error (SE) formula of: SE(FSDH) = FSDH/√(2N – 2) '
L540: 'The uncertainties associated with FSDV and FSDH+V are estimated via a boostrapping approach: the metrics are re-calculated 100 times after (with-replacement) resampling in order to find the variability of each pixel's excess kurtosis (FSDV) and shannon entropy (FSDH+V). The standard deviation is taken as the sampling uncertainty on each metric.

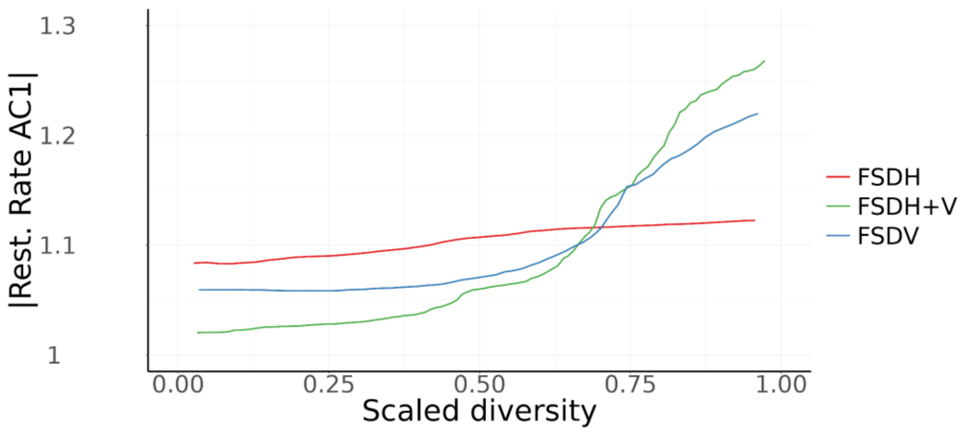
The propagation of the uncertainties associated with the remote inputs through the framework is discussed in the updated line (L634):
'Uncertainty in the models is estimated by bootstrapping a further 100 samples from the training dataset.' ->
'Uncertainty in the models is estimated by bootstrapping a further 100 samples from the training dataset, with the FSD metric values in each model randomly sampled from a normal distribution

with standard deviation as the estimated associated error. The uncertainties associated with the limited sampling of the FSD metrics are expected to dominate the overall uncertainty, and therefore uncertainties associated with non-remotely sensed inputs (such as the ERA5 climate model variables) are not included in the analysis.'

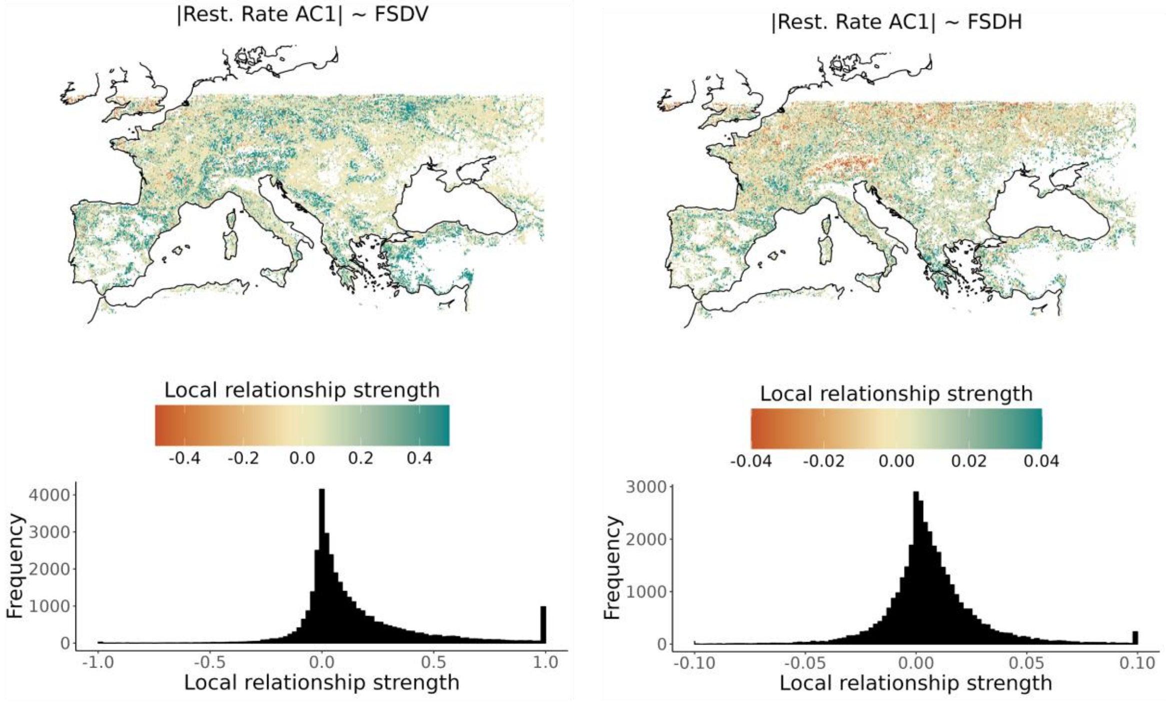
Second, one of the key conclusion of this study is more importance by vertical structural diversity than horizontal structural diversity in contributing to resilience. Estimate of horizontal structural diversity vs vertical structural diversity may depend on the spatial scale. In particular, the horizontal structural diversity could be relatively high in drier regions which would depend on spatial scale. Thus, I am curious whether and how the spatial scale of data analysis could influence the results across rainfall gradient.

We agree that both the resilience and diversity metrics are both dependent on the scale at which they are measured. Part of the reason we chose to use 0.05 degrees is that there are many studies currently in the literature at this resolution and therefore our study fits and is comparable with these. Additionally, during preliminary studies we found there to be a significant amount of noise in the kNDVI temporal autocorrelation at higher resolutions (e.g. 1km and below). We theorised that this is likely due to spatial heterogeneity affecting the MODIS footprint (https://www.sciencedirect.com/science/article/abs/pii/S0034425721002145).

Following your suggestion, we chose to rerun the analysis at 0.1 degrees resolution. This involved recomputation of the FSD and resilience metrics at 0.1 degrees and re-running the analysis steps (we did this without including the uncertainty bands). This is added to the manuscript for the AC1-derived restoration rate only, in order to save space (the same pattern is seen in the variance-derived restoration rate and we are happy to provide it, if required) (L661):
'In order to support the analysis and assess the impact of resolution on the model relationships, the random forest inputs are also recomputed at 0.1◦ and the analysis re-run (without computation of the corresponding uncertainties). The results are shown in extended data E.'

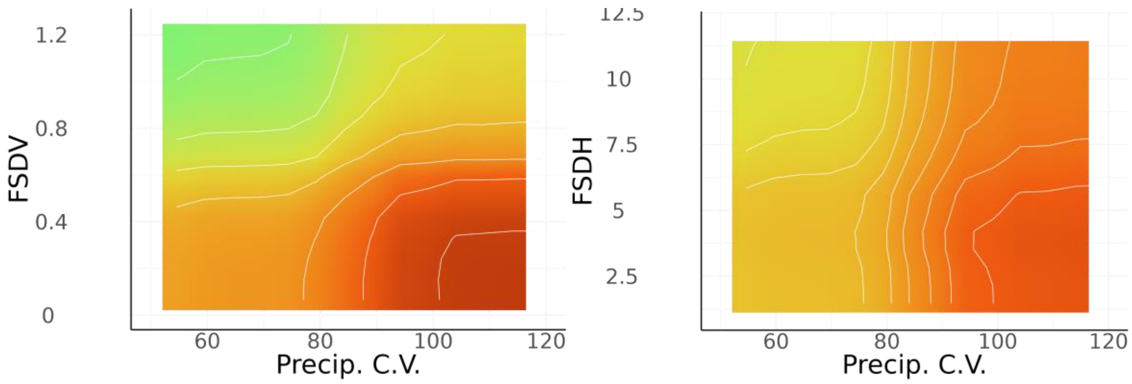


The results generally show the same pattern: an increase in FSD is associated with higher resilience, with the FSD metrics in the same order as previously. To the discussion we have added the line (L303): The analysis is also conducted at two different spatial resolutions, with the overall results remaining consistent at both 0.05° and 0.1° .



In terms of differences in spatial patterns in the strength of the resilience relationship, it is broadly similar at the two different scales, however there are some regional differences between the scales. For example at 0.1 there is an inverse relationship between resilience and FSDH in the alps (compared to 0.05). There is likely increased rainfall and a higher rainfall gradient (e.g. between high and low altitude) in this region. It is also an area of (relatively) higher FSDH than FSDV (though this could be affected by many things, such as lower tree height at altitude). As we move to a coarser resolution (0.1) and likely average out the relatively higher level of FSDH, we are changing the resilience-diversity relationship.

In order to aid and investigate further the relationship between rainfall gradient and resilience we additionally produce the following 2d partial dependence figures the FSDH and FSDH relationship with resilience, as a function of the coefficient of variation in rainfall (at 0.05). We have not added these figures to the updated manuscript as it is more to aid with this question.



Third, resilience is a concept with temporal response to disturbance. This study examined the spatial relationship between resilience and structural diversity and other climate variables.

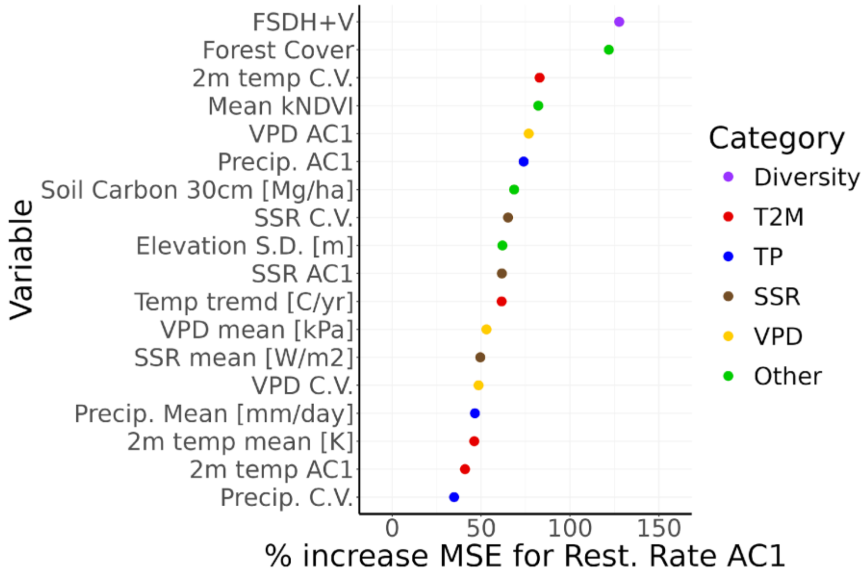
We agree that resilience is a temporal response to disturbance. In the study we assess the temporal response of kNDVI to disturbance in a temporal timeseries of 19 years for each pixel (utilising temporal variance and temporal autocorrelation metrics to derive the recovery rate for each pixel). We then deconstruct the temporal recovery rates by the spatially-distinct local environmental conditions. This process enables the comparison of the recovery rates by incorporating local environmental data (which might drive differing local response rates). Thus the study is a measure of large-scale temporal response to disturbances (resilience) that accounts for spatially distinct local factors to examine the spatial relationship between (temporal) resilience and structural diversity.

In order to clarify this point, we have made the following changes:
L87 '*AC1- and variance-derived resilience metrics are developed from kNDVI observations*
-> AC1- and variance-derived resilience metrics are developed from a 0.05◦ and 8-day kNDVI time series …'
L90 'A machine learning model isolates these FSD-resilience relationships from confounding environmental factors enabling a deeper understanding of the local and Europe-wide relationships'
-> 'A machine learning model isolates these FSD-resilience relationships from confounding, spatially-distinct, environmental factors enabling a deeper understanding of the local and Europe-wide relationships'

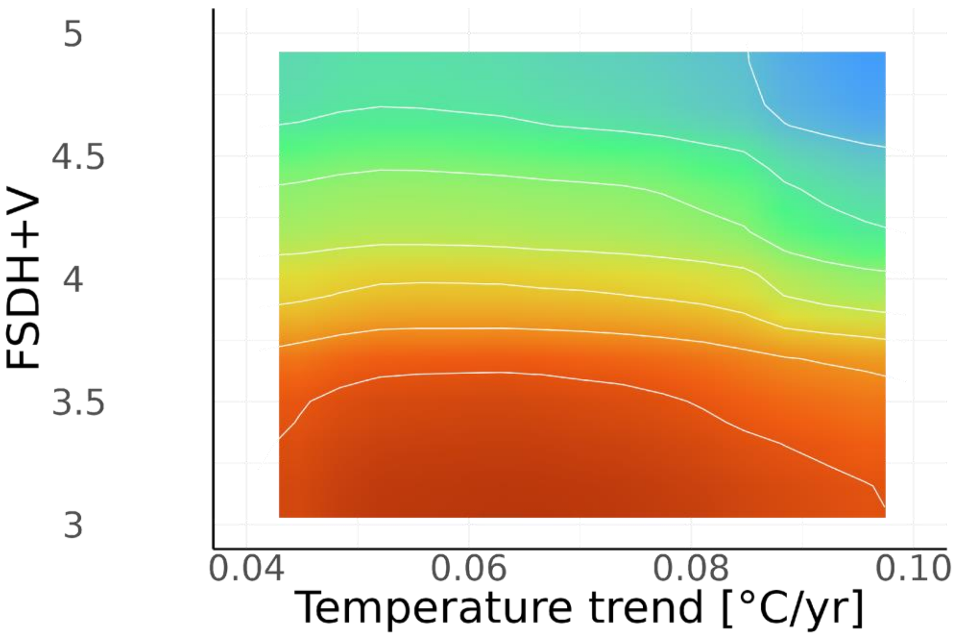
In figure 5 and section 'under climate warming', I am curious whether the rate of climate warming instead of 2m temp mean could be used. Moreover, N deposition seems to be an important variable as well.

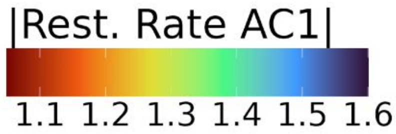
In order to investigate the effect of the rate of warming in the model we reran the model incorporating the deseasonalised 19-year temperature trend at each pixel into the input dataset (i.e. the pixelwise warming trend over the last 19 years as observed in the deseasonalised ERA5-

Land reanalysis data). It should be noted that in temporal resilience analyses, the data is normally detrended both seasonally and in terms of the overall long term trend in order to isolate changes in short term resilience and temporal autocorrelation. We find that the warming trend is a moderate predictor of resilience in European forests. It should be noted however that it likely 'borrows' some of the 'model importance' from the mean background temperature in the importance figures, which decreases in importance as can be seen below, due to collinearity between the two).



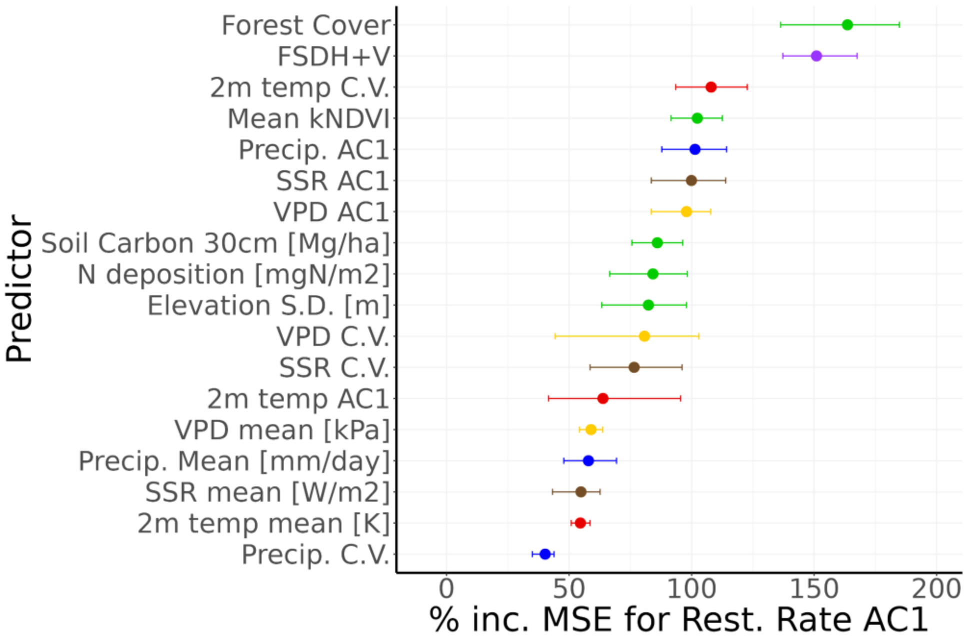
We have re-run figure 5 with the trend in temperature as the x-axis. There is relatively little dependence of the resilience on the temperature trend (i.e. the resilience is not lower in areas which are warming faster – though to be clear this figure in its current form does not say anything about whether areas that are warming are exhibiting faster declines in resilience). Therefore as there is relatively little dependence of the resilience on recent temperature trends we choose not to include this figure.



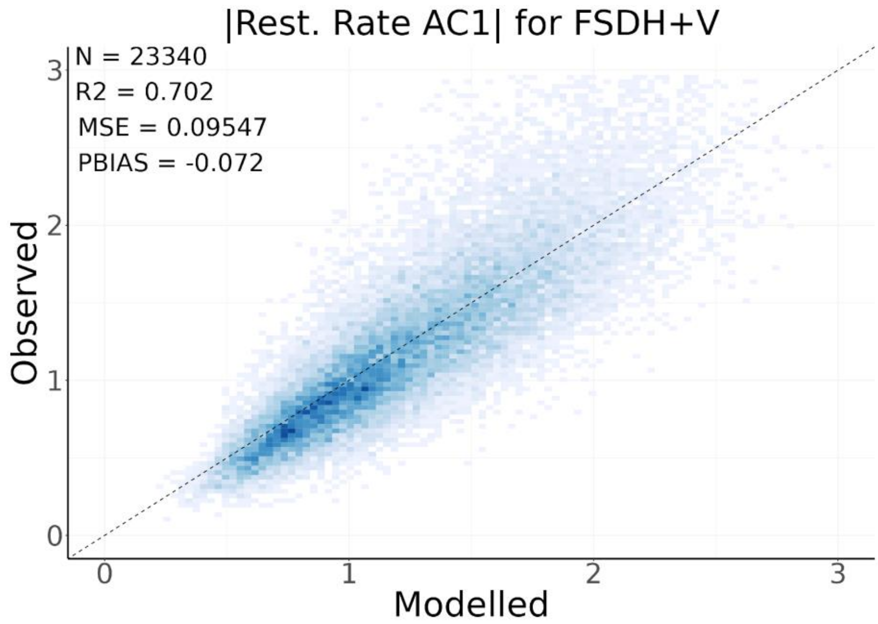


Finally we added Nitrogen deposition to the model. This was done using the N-deposition data from https://www.emep.int/mscw/mscw_moddata.html (summing the wet and dry deposition data (Total deposition of reduced nitrogen = Dry+Wet RdN = *DDEP_RDN_m2Grid+WDEP_RDN*) and taking the mean total N-deposition over the years 2013-2018 for a representative average.

The variable has reasonable importance - as measured through the effect on the increase in MSE. It on the lower end of importance (slightly below soil organic carbon content). This can be seen in the following importance figure (for shannon entropy vs Rest. Rate AC1):



When included in the model the prediction capability increases slightly (though not significantly) as measured through increase in R2 and decrease in MSE in the test data. Ndep also has low collinearity:



There is no major change in the findings of the paper. However, due to the increase in model performance, moderate importance as a predictor, and low collinearity with other predictors, we include it as a predictor in the analysis. We have rerun the figures with it included and adding the information regarding its inclusion in the paper. Therefore note that some of the numbers and figures in the updated paper will be slightly different reflecting this change. I have added information on the dataset in L497:

'Nitrogen deposition data are taken from the EMEP Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components 2024 status report and are available at 0.1◦ resolution. The nitrogen deposition is taken as the total annual sum of reduced (wet and dry) nitrogen deposition, interpolated to 0.05◦ and averaged over the period 2013-2018 [81].'

I also have the following very minor suggestions to improve this study

Figures: may consider adding a compass and latitude and longitude to each map

Thanks – we are happy to add a latitude and longitude lines to the maps and this makes the need for the compass redundant.

Line 53: could delete 'through'

> well spotted! Done

Lines 83-92: some more details on how the AC1 is estimated would be useful, i.e., in term of spatial and temporal scales and in response to what types of disturbance.

> Thanks for this suggestion which makes the details clearer in the introduction. We have replaced the line:

'In this paper, we assess the relationship between resilience and FSD in Central and

Southern European forests. AC1- and variance-derived resilience metrics are developed from kNDVI observations, whilst the work utilises three separate'
->
In this paper, we assess the relationship between resilience and FSD in Central and Southern European forests. AC1- and variance-derived resilience metrics are developed from a 0.05◦ and 8-day kNDVI time series, whilst the work utilises three separate …'
> It should be noted that whilst the study is done using 0.05◦ and 8-day kNDVI data, that data is itself aggregated from 500m daily MODIS data (as explained in Methods: Vegetation Data).

Regarding the types of disturbance, the metrics are not disturbance-specific, instead utilising information contained in the internal fluctuations of a system to gain insight into the system's response to external influences (a good summary is found in ref 19m, section 4: Ecosystem resilience monitoring and early warning using earth observation data: Challenges and outlook. https://doi.org/10.1007/s10712-024-09833-z)

> We discuss this in the introduction (L50-L56), including citing the above article, however we could make this clearer. We have therefore added 'proxies for the recovery rate from larger perturbations and disturbances [19]' to these lines (L50-L56):
Recently, critical transition theory has developed early warning signals as natural systems approach bifurcation points, where the equilibrium-restoring forces of the system to natural perturbations weaken [18–21]. A critical slowing down is observed through through rising 1-lag AutoCorrelation (AC1) (the correlation between consecutive points in a time series) and variance in the system response to small perturbations, indicators that function as proxies for the recovery rate from larger perturbations and disturbances [19, 21, 22].

> Please let us know if you would like further clarification

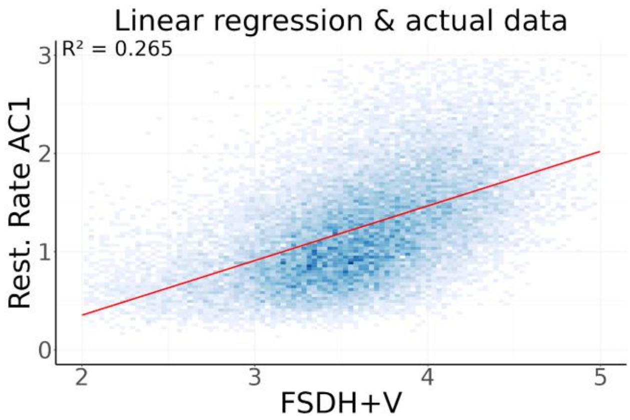
Line 129-132: this difference may be related to rainfall gradient with potential higher horizontal diversity in drier regions.
> Yes this could be the case. We have altered the line such that it reads:

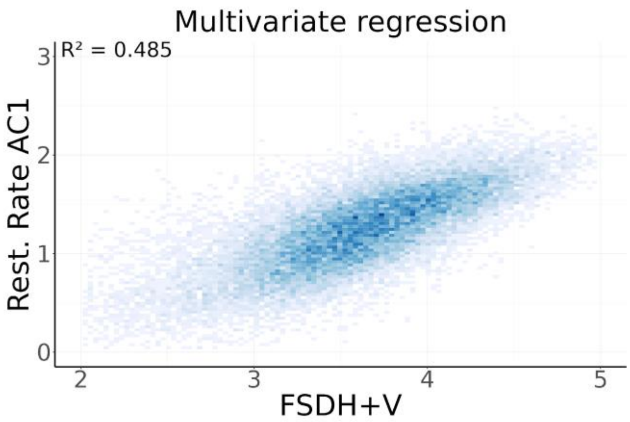
'*However, there is variability between the FSD metrics and correlation between them is low. For example we observe that areas with high horizontal structural diversity do not necessarily have high vertical diversity, and vice-versa, potentially driven by the effect of precipitation on canopy complexity [ref https://www.nature.com/articles/s41467-020-20767-z]'*

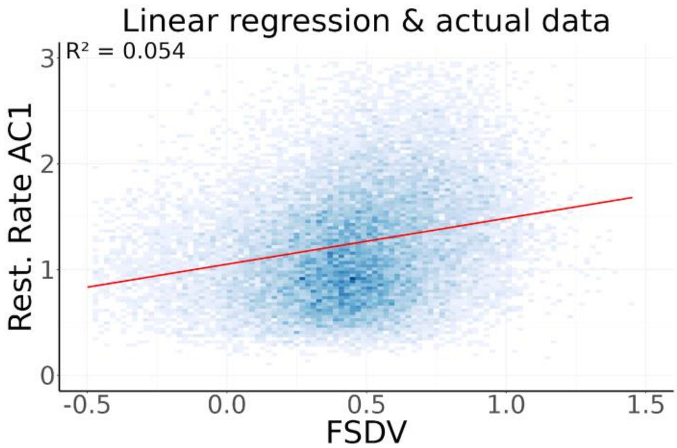
Adding also a reference relating rainfall to canopy structural complexity: 'global variation of forest structural complexity is largely explained by annual precipitation and precipitation seasonality', https://www.nature.com/articles/s41467-020-20767-z.

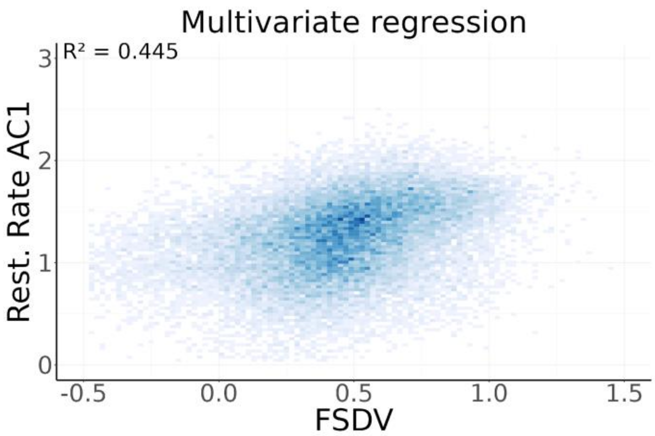
Section on random forest models: may consider having linear analysis as well with explicitly accounting for interaction of structural diversity with climate (i.e., temperature/warming).

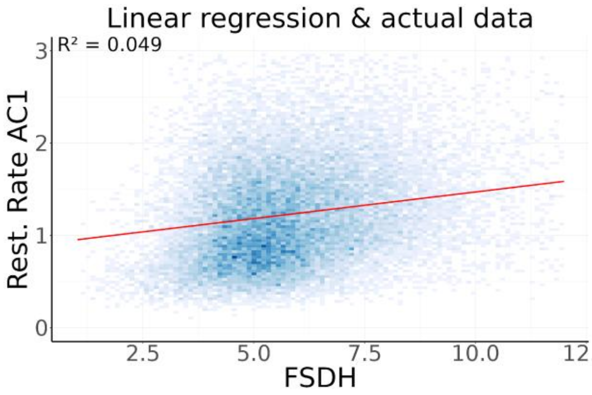
We have run a linear and multivariate regression analysis in addition to the random forest and have now added the results to the supplementary information. Whilst the ‘simple’ linear regression (below left, red line superimposed on the actual data for the test dataset) only accounts for the FSD metrics, the multivariate regression (below right, figure shows the FSD metric & predicted Rest. Rate for the test dataset) also accounts for all the variables used in the RF. Additionally we have run a multilinear regression on a subset of the top 5 most important variables (as measured from the random forest importance) in order to reduce collinearity, though for simplicity we do not include this in the supplementary information. Whilst the same general trend is observed between the FSD metrics and the restoration rates, the linear regressions have a lower performance than the random forest as measured through the R2, particularly in the case of the FSDV and FSDH metrics. The regressions are shown for the AC1-derived restoration rate, however we also have the variance-derived restoration rate is required (it looks very similar, with a slightly lower R2). All the figures support the conclusions of the main analysis.

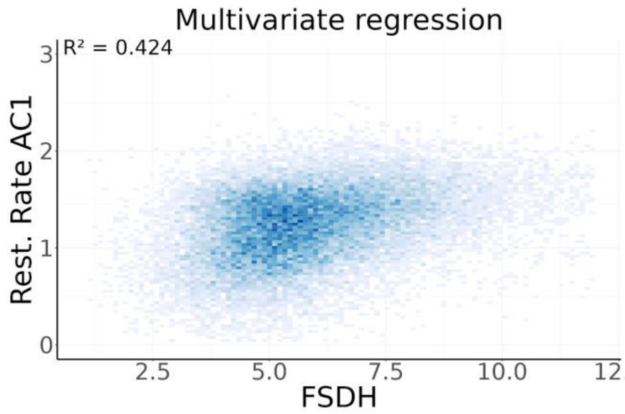












We include these figures in the supplementary information and reference the supplementary information in the methods 'The Random Forest model' section in the line (L639):
Extended data B, show metrics for the performance of the different models in replicating the observed restoration rates… Meanwhile extended data C displays equivalent simple linear and multivariate regressions produced in support of the RF models.'

Line261：use"offset" instead of "compensate for"

Done. This section has been rewritten but the comparable phrase is reworded.

Discussion: may discuss a bit about the caution of using AC1 and/or variance as indicators of resilience. Previous studies have showed lack of early warning signals with regime shift, i.e., by rate induced tipping (Huang et al., 2024) and also variance as a better predictor for stochastically driven abrupt transition (Chen et al., 2018).

References: Huang et al. 2024. Deep learning for predicting rate-induced tipping; Chen et al., 2018. Rising Variability, Not Slowing Down, as a Leading Indicator of a Stochastically Driven Abrupt Transition in a Dryland Ecosystem

Thanks for this insight we agree that it is important to make clear that whilst our results hold for bifurcation tipping (B-tipping) it is not so clear (an area of debate and uncertainty) whether or not AC1/Variance/Rest. Rate holds for noise-induced (N-tipping) or rate-induced tipping (R-tipping). Some sources suggest that the AC1/Var EWS can be used for R-tipping (' Generic early warning signals [temporal AC1/Var] predict when the system is close to rate-induced tipping' https://link.springer.com/article/10.1007/s10021-021-00610-2) however as you point out, it is an area of uncertainty and we should discuss this. Similarly - as you point out - some sources suggest that EWS are less likely to work for N-tipping, or that variance would be more important. It is important to note that some studies (with different conditions of course) prefer instead AC1 (https://esajournals.onlinelibrary.wiley.com/doi/10.1890/11-0889.1 'We show both analytically and in simulations that variance may sometimes decrease close to a transition…. By contrast, *autocorrelation always increases toward critical transitions in our analyses') . It is for this reason that we sought to include both AC1- and Variance metrics in our results, with both showing similar patterns in the relationship between resilience and diversity in forests.*

In L319 (Discussion of the limitations of the results) we have added the lines (and incorporated the sources):
It is also important to note that whilst temporal AC1- and variance-based indicators have demonstrated utility as early warning signals in bifurcation-induced tipping points - whereby gradual changes push the system to a threshold point between two regimes - there is some debate over their utility for other tipping scenarios [18, 22, 40]. Noise-induced tipping scenarios - driven by stochastic forcing and without accompanying change in drivers - are, by definition, less predictable and therefore less likely to exhibit critical slowing down, though rising variance may still be an useful predictor of transition [45]. In rate-induced tipping - whereby the pace of change is too rapid for the system to track its stable state - some studies support the utility of traditional early-warning signals, whilst others suggest alternative approaches, e.g. via deep learning, may be more appropriate [46, 47].

Line621：the sentence"The Random Forest uses 500 trees and 7 variables sampled at each split, chosen via a 10-fold cross-validation optimization process." could be refreshed as "The Random Forest model comprises 500 trees, with 7 variables sampled at each split, as determined by a 10-fold cross-validation optimization process."

> Agreed, and done.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

satisfied with the revise

Reviewer #2 (Remarks to the Author):

The revised manuscript has largely addressed my previous suggestions in term of robustness of results, spatial scale et al. I am also highly impressive by the findings with insightful discussions of this interesting study. It is good to learn that diversity in canopy complexity is a better predictor of resilience than spatial variability in canopy height.

Here I only have minor suggestions for the authors to consider.

Abstract lines 24-29: if possible, may consider simplifying the presentation of methods which would save the number of words if there is word limit in abstract.

> I had understood the word limit to be 200 words, but it seems on the editorial request table it is 150 words. I would prefer to leave the original abstract, but if over the limit, then following this suggestion, I suggest changing the abstract to:

Ecosystem resilience represents the capacity to withstand and recover from perturbations, an important property for ecosystem function in an era of escalating disturbances. Whilst studies relate large-scale forest resilience to abiotic factors, knowledge gaps remain regarding the link to aspects of functional diversity, such as forest structural diversity (FSD), a factor controllable through management.

Here we use spaceborne lidar-derived FSD to quantify its role in determining resilience in Southern and Central European forests. A random forest isolates the FSD-resilience interplay by disentangling confounding environmental factors.

Results show a positive FSD-resilience relationship in 80% of forests. Canopy complexity is a better predictor of resilience than spatial variability in canopy height. This emergent relationship is explored as an adaptation measure to preserve resilience under warming scenarios, with the decline associated with 1°C of warming compensated by a 10% increase in canopy complexity. The findings suggest that management promoting canopy complexity potentially compensates warming-driven declines in resilience.

Lines 45-46: this sentence could be improved, i.e., ‘decline of forest resilience under increasing global change and disturbances with rising tree mortality…’

> Thanks. Changed to: ‘However, recent evidence shows a decline of forest resilience under increasing global change and disturbances, with rising tree mortality in Europe, particularly from drought-driven bark beetle infestations...’

Lines 51-52: perhaps ‘as natural systems approach bifurcation points’ could be rephrased to ‘to detect the bifurcation points of natural systems’

> Thanks: ‘Recently, critical transition theory has developed early warning signals to detect the bifurcation points of natural systems,’

Lines 290-292: may consider suggesting that this pattern may be different in dryland forests

> Thanks. I think it might be out of place to add this into the text here. The sentence (Lines 290-292) is summarising the general differences between the different FSD metrics at Europe-wide scale found in the analysis and we did not do this break down of results in the analysis.
Whilst we did show a map of general spatial patterns we haven’t specifically looked at particular forests (e.g. dryland forests). Hopefully we covered this in the statement (L316): ‘Additionally, the RF model displays averaged conditions, which may not always hold at local levels, for example across uncommon or extreme climate domains or specialised forest types, and where there is more limited training data.’ where I have now added ‘climate domains or specialised forest types, and’. Additionally, throughout we try to stress that here we are considering ‘large-scale’ relationship, e.g. L405 ‘Indeed, a recent review of natural disturbance forest management strategies suggests that whilst situation-specific evaluation of effectiveness of adaptation is important, a new research avenue of large-scale experiments is required to address ‘tipping point management’.

Line 327: could add ‘that’ before ‘alternative’

> Done