

Future enhanced threshold effects of wildfire drivers could increase burned areas in northern mid- and high latitudes

Corresponding Author: Professor Zhengxiang Zhang

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 Professor Zhang,

Your manuscript titled "Enhanced Threshold Effects of Drivers Promote Future Wildfire Changes at Mid–High Northern Latitudes" 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.

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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,

Erika Buscardo, PhD
Editorial Board Member
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript explores the nonlinear responses of wildfires to environmental change. In particular, it focuses on identifying and quantifying threshold effects in parameters governing wildfire responses in the mid-high northern latitudes (> 30°N). Specifically, the authors quantify apparent threshold behavior at a 0.25° resolution from a collection of data encompassing

the 2001-2022 time period. Subsequently, they extend their work using future climate simulation datasets under 4 socio-climate scenarios to project and compare expected future burned area (BA) of the region for 2030-2100 when accounting for the various parameter threshold effects. Overall, the study aims to address three key questions: (a) What spatial patterns do the thresholds and threshold effects of wildfire drivers exhibit? (b) What key role do threshold effects play in wildfire driver interactions? (c) How will wildfires respond to climate change under the influence of threshold effects? The focus on identifying quantifiable thresholds and threshold effects is novel and potentially critical for understanding ongoing changes and managing future burned area outcomes. The manuscript is well written and structured clearly despite describing complex phenomena.

Specific comments include:

1. While the manuscript clearly states that it is focused on the mid-high ($> 30^{\circ}$) latitudes of the northern hemisphere, it begs the question of why this apparently arbitrary division was selected? Were there data limitations or other constraints for $< 30^{\circ}\text{N}$?
2. Line 44 (and elsewhere) "hydrothermal" – I do not believe that this is being used correctly here as it is generally used for describing hot water in geologic or ocean settings. It is not clear exactly what it is referring to in the manuscript.
3. Lines 128-129 – Monthly fire weather index (FWI) data can only weakly correlate to the actual wildfires unless the fires persist for the whole month. It certainly doesn't "assess the impact of weather conditions on wildfires". I can see the attraction for using the data but they are more of a fire season indicator than fire weather when averaged over a month of day/night, rain/shine, cool/hot conditions. FWI is conceived of as a daily indicator of potential fire intensity. If used, this has to be more clearly indicated as being averaged monthly FWI or termed something like average seasonal intensity.
4. Line 137 – shouldn't the land cover change (LCC) data extend to 2022, not end at 2021?
5. Lines 140-141 – How were 2020-2022 dealt with for the missing GDP data?
6. Lines 165-166 – Are these averaged fire seasons for the 2001-2022 time period or are the fire seasons independently variable by year? Beyond variability, the seasons presumably have been extending over time during the study period as well and certainly will in the future climate scenarios.
7. Lines 177-178 – Were the training/testing/validation data randomly placed by pixel or spatially stratified in some other way?
8. Lines 205-206 – It is not clear how the Pearson's correlation coefficients were used to explore "analogous spatial patterns". Were correlations between all variables examined at a 0.25° scale or as classes?
9. Figure 1 panel c – Why is e (dashed line) set at ~ 8 for all cases?
10. Figure 2 – How is this interpreted? I am confused especially by Pop and LCC. What is signified by STMS Pop (j) which has a threshold effect that is substantially below the average e (i.e. blue line), but has a strong enhancing threshold effect (red with cross in the circle), however it is located at a negative value on the x axis? Please explain. Why is e average set to the top of the regional average range in all cases? Is there any way to derive the net effect of all the drivers for an ecoregion (e.g. polar)? Are they additive? Note too that FWI is mostly a weakening effect because it is actually a monthly average not a true FWI comparison.
11. Figure 3 – need to correct the spelling of Temperature in panels b and f.
12. Lines 303-305 – Instead of just saying that all these regions had threshold effects $>30.37\%$ provide the values in parentheses after each region name so the reader can see if the differences are marginal or substantial. Likewise, do the same for lines 304-305, provide the values for the regions below 28.39% .
13. Lines 318-320 – What does it mean to dominate wildfires? I assume that you mean that it is the strongest explanatory variable...
14. Lines 321-324 – Dominated again. FWI should make clear this is a monthly average or have a revised name. Misleading as presented.
15. Lines 324-325 – "controlled wildfires" – what does that mean? Does $\sim 29\%$ signify control? Weren't the drivers more important? These were certainly substantial contributors but not the main ones.
16. Figure 5 – FWI_FS_TE looks to be much more important among threshold effects in this figure than would seem warranted in figure 4. Conversely Pre_FS_TE looks much less important here than in figure 4. What is the explanation?
17. Lines 407-410 – Can you provide an example from the results to illustrate this phenomenon or that supports this contention?
18. Lines 431-433 – "reduce the overall increase drop" – not clear what that is supposed to mean. Also, the results seem to show considerable variance in the scenario responses with some areas having reduced BA for higher emission scenarios. Some nuance to the description as compared to overall regional averages is warranted.
19. Lines 439-440 – Somewhat misleading to state it in this way since all $<30^{\circ}\text{N}$ land area for the hemisphere is not included and the tropics have more burned area than either the boreal or temperate regions.
20. Lines 456-459 – Ok, stated well but why is there no consideration that additional thresholds may exist that were not reached in the early 21st century but could be in the coming decades under the climate change scenarios? Surely it is not presumed that all possible thresholds have been discovered in this work based on climate change experienced to date?
21. Lines 466-467 – Geographical differences such as what? The only element that was described was latitude.
22. Figure S1 – Why are there 2-8 models used for each panel but 6 are used in the main text?
23. Supplement Line 80 – "donates" should probably be 'denotes'.
24. Supplement Lines 99-101 – since more pairwise relationships weakened the BA than strengthened it, what is the reason for the net increase in BA. Is this caused by the magnitudes of the relative weakening and strengthening relationships and/or the respective areas of relevant ecoregions where the net effect was to increase/decrease BA?
25. Supplement Lines 136-141 – threshold addition improved BA explanatory power by 1.6% and test RMSE by 0.23 . The text states that this significantly improved interpretability but was there any actual test for significance? The results are improved but not tremendously.

Reviewer #2 (Remarks to the Author):

“Enhanced Threshold Effects of Drivers Promote Future Wildfire Changes at Mid-High Northern Latitudes” presents a comprehensive analysis of the threshold effects of various climate and population variables on the effects of burned area across mid-high northern latitude ranges, as well as making broad forecasts of potential fire activity using these threshold effects to the end of the century. Overall, the content of the paper and its methodology is sound, the paper follows a logical structure, the results are backed up with reasoning and all the figures and tables are relevant. Commentary is supported by a good number of references and soundly follows from the results. The statistical analysis is comprehensive; several variables and tests are used to ensure the validity of the investigation, and the process is well documented either in the main body of the text or in the supporting material to ensure the work is reproducible. The findings are novel, relevant, and important for future work. There are no issues with the English language. I have a handful of very minor comments and suggestions and, if these are dealt with, I would recommend subsequent publication.

Minor comments:

L. 116 – you extend the BA time series for 2021 and 2022 using MCD64A1 (and other products) “via methodologies similar to those used by the dataset producers”. In Eurasia especially, MCD64A1 has been found to significantly underestimate FireCCI51 (see Clelland et al., Annual and Seasonal Patterns of Burned Area Products in Arctic-Boreal North America and Russia for 2001-2020, Remote Sensing, 2024, 16(17), 3306). As such these two years could underestimate the total BA. I would either state this as a limitation, or provide more evidence that your extension is a reliable continuation of the previous FireCCI51 dataset, as the current explanation seems vague.

L. 165 – you “calculated the multiyear average BA for each calendar month” – is this for each grid cell and/or ecoregion? It’s not quite clear.

Fig. S2 – The first time we see use of the different ecoregions is Fig. S2 (first mentioned line 166), yet the abbreviations aren’t defined until Fig. 1 (line 213). I suggest either repeating the ecosystem names in the caption for Fig. S2 or introduce them earlier in the methods section.

L. 307 – You don’t mention what happens between latitudes 30-35°N, 42-47°N, or higher than 60°N. For the two regions you talk about – are these results the strongest and weakest contributions of the different latitudes?

Fig. 6(a)-(f) – The units of km² seems small to me considering the values. Please check.

L. 397 – “although...increase”. This seems an obvious point without further expansion. Consider removing.

L. 418 – “Warming and drought...transport changes”. I agree this is an important clarification statement, but you don’t expand on the causes of high latitude fires elsewhere, so this sentence seems a little out of place.

Throughout – the paper is excellently written; however, it occasionally may not always be understandable for people without a prior background knowledge of climate/fires/statistics. Before resubmission, consider asking a non-expert to read through the paper to point out potentially more confusing points which may need rewording.

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Decision Letter:

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Dear Professor Zhang,

Your manuscript titled "Enhanced Threshold Effects of Drivers Promote Future Wildfire Changes at Mid–High Northern Latitudes" 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,

Erika Buscardo, PhD
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Alienor Lavergne, PhD
Senior Editor
Communications Earth & Environment

Mengjie Wang, PhD
Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have done a superb job in providing clear and detailed responses to my previous comments. The work is novel and important for interpreting ongoing changes in burned area for higher latitudes (>30 degrees). The corresponding edits should make the manuscript clearer and more accurate. I have no further comments or issues with the manuscript and look forward to seeing it in print.

Reviewer #2 (Remarks to the Author):

Thank you for taking the time to reply to my comments. I am satisfied with the responses and have no further significant suggestions, although would like to comment on your Response 5 and highlight a couple of typos or word changes for your consideration.

Comment to author Response 5. Thank you for the clarification. I just wanted you to double check the numbers were accurate, so the additional clarification in Figure 6 probably isn't necessary as the units are given in the figure itself.

Typos or word changes:

L. 67 – “landscape scale” sounds clunky. Consider “local” instead.

L. 68 – “fire behavior” tends to be singular rather than plural.

L. 123 – Consider replacing “finally” with “ultimately”.

L. 451 – “Currently” doesn't sound quite right. Consider “Warming and drought have intensified”.

Table S1 – The units of “Leaf Area Index” are either m^2/m^2 or $m^2\ m^{-2}$, not m^{-2}/m^{-2} . This occurs twice in the table.

Table S1 – “FOA Global Ecological Zones” should be “FAO ...”

Appendix S2 doesn't appear to be referenced in the main text.

Table S4 – L. 111 – “Yellow the dashed line” should be rephrased.

Figure S6 – L. 136 – Consider “comparison” instead of “comparing”

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Response to Reviewer #1 Comments

Reviewer #1

The manuscript explores the nonlinear responses of wildfires to environmental change. In particular, it focuses on identifying and quantifying threshold effects in parameters governing wildfire responses in the mid-high northern latitudes ($> 30^{\circ}\text{N}$). Specifically, the authors quantify apparent threshold behavior at a 0.25° resolution from a collection of data encompassing the 2001-2022 time period. Subsequently, they extend their work using future climate simulation datasets under 4 socio-climate scenarios to project and compare expected future burned area (BA) of the region for 2030-2100 when accounting for the various parameter threshold effects. Overall, the study aims to address three key questions: (a) What spatial patterns do the thresholds and threshold effects of wildfire drivers exhibit? (b) What key role do threshold effects play in wildfire driver interactions? (c) How will wildfires respond to climate change under the influence of threshold effects? The focus on identifying quantifiable thresholds and threshold effects is novel and potentially critical for understanding ongoing changes and managing future burned area outcomes. The manuscript is well written and structured clearly despite describing complex phenomena.

Response to reviewer #1 comments:

We sincerely appreciate your thorough and insightful review of our manuscript. Your valuable comments and suggestions have significantly improved our work. We also appreciate your recognition of the novelty and significance of our study, along with your encouraging feedback on the quality of our analysis and writing. In response to your recommendations, we have revised the manuscript accordingly. Below, we provide point-by-point responses to your comments. Each response includes: your comment (in red), the original text (in black), our response (in blue), and the revised text or figures (in black) with corresponding pages and line numbers. Some additional necessary revisions were also made to enhance the manuscript's clarity and coherence. Here, we have provided a separate document with tracked changes (red text), using yellow highlighters to mark all modifications made based on your feedback. We sincerely hope that our responses and the revised manuscript meet your expectations.

Specific comments:

Comment 1: While the manuscript clearly states that it is focused on the mid-high ($> 30^\circ$) latitudes of the northern hemisphere, it begs the question of why this apparently arbitrary division was selected? Were there data limitations or other constraints for $< 30^\circ\text{N}$?

Response 1: Thank you for your question regarding our study area. We clarify that regions south of 30°N of the northern hemisphere have no restrictions on data availability. We focused on the mid-high ($> 30^\circ$) latitudes of the northern hemisphere as the study area, due to their distinctive regional characteristics and global demonstrative significance for understanding wildfire and climate change (*Fig.R1 a*). The main reasons have already been stated in the last paragraph of the introduction section (**Page 6, Lines 98-106**). Other complementary reasons include the following:

- (1) The frequency of extreme wildfire events (≥ 99.99 th percentile) increased by 2.2-fold from 2003 to 2023, with the highest frequency and increasing trends in the region north of 30°N (*Fig.R1 b*). Wildfire response to external drivers is shifting from gradual patterns to abrupt changes. Thus, the choice of mid-high ($> 30^\circ$) northern latitudes is not arbitrary, because this region facilitates the explanation of such nonlinear wildfire response and the threshold effects of drivers.
- (2) Some recent studies highlight that the mid-high ($> 30^\circ$) northern latitudes are representative regions for examining the dynamic interactions among wildfires, climate change, and the carbon cycle. For example, *Zhao et al.* identified this region as a typical area for exploring wildfire dynamics, their contribution to biogeophysical processes, and the feedback mechanisms of wildfires in response to climate change.
- (3) Previous studies on the threshold effects of wildfire drivers focused on high-latitude tundra, or on comparing threshold differences between continents in the tropics alone (*Young et al, 2019; Alvarado et al, 2019*). We believe that the wildfire regimes in the tropics and non-tropics are distinct, and integrating them in a single study may lead to biased results, hindering the identification of threshold effects. Our subsequent work is working to address these issues, but this paper only focused on the mid-high ($> 30^\circ$) latitudes of the northern hemisphere.

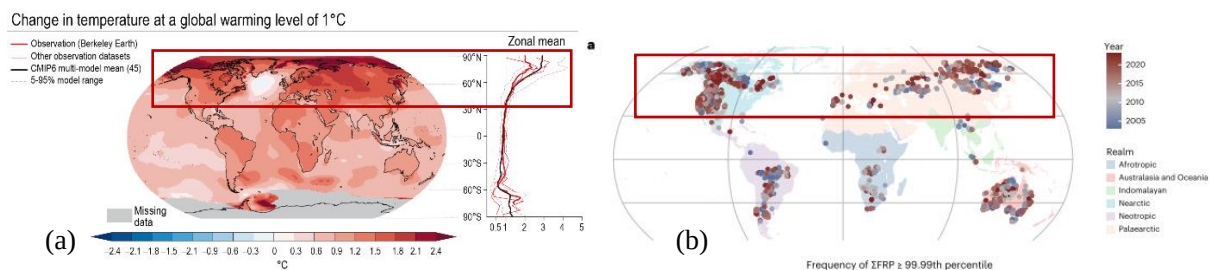


Fig. R1. Global warming on the mid-high ($> 30^\circ$) latitudes of the northern hemisphere (*IPCC 2022*); Distribution and trends of the most extreme wildfires on Earth (*Cunningham et al. 2024*).

References

- [1] Cunningham C.X., Williamson G.J., Bowman D., 2024. Increasing frequency and intensity of the most extreme wildfires on Earth. *Nat. Ecol. Evol.* 8. <https://doi.org/10.1038/s41559-024-02452-2>.
- [2] Zhao J., Yue C., Wang J., Hantson S., Wang X., He B., et al., 2024. Forest fire size amplifies postfire

land surface warming. *Nature*. 828-834. <https://doi.org/10.1038/s41586-024-07918-8>.

- [3] Alvarado S.T., Andela N., Silva T.S.F., Archibald S., Poulter B., 2019. Thresholds of fire response to moisture and fuel load differ between tropical savannas and grasslands across continents. *Glob. Ecol. Biogeogr.* 29, 331–344. <https://doi.org/10.1111/geb.13034>.
- [4] Young A.M., Higuera P.E., Abatzoglou J.T., Duffy P.A., Hu F.S., Gillespie T., 2019. Consequences of climatic thresholds for projecting fire activity and ecological change. *Glob. Ecol. Biogeogr.* 28, 521–532. <https://doi.org/10.1111/geb.12872>.

Comment 2: Line 44 (and elsewhere) “hydrothermal” – I do not believe that this is being used correctly here as it is generally used for describing hot water in geologic or ocean settings. It is not clear exactly what it is referring to in the manuscript.

[Page 3, Line 44-46, Abstract]

Wildfire-driver thresholds, coregulated by gradient differences in hydrothermal conditions, vegetation productivity, and human activities, effectively explain the spatial patterns and uneven responses of mid–high latitude wildfires.

Response 2: We fully agree with you and have replaced all “hydrothermal conditions” with “heat and moisture conditions” in the manuscript. This term refers to the combination of moisture and heat that affects geographic processes and ecosystems and can reflect the overall character of a region's water and heat supply.

[Page 3, Line 44-46, Abstract]

Wildfire-driver thresholds, coregulated by gradient differences in **heat and moisture conditions**, vegetation productivity, and human activities, effectively explain the spatial patterns and uneven responses of mid–high latitude wildfires.

[Page 7-8, Line 131-133]

We selected 2 m air temperature and total precipitation to measure **heat and moisture conditions** and combined them with 2 m dewpoint temperature to calculate the atmospheric vapor pressure deficit (VPD) from the ERA5 dataset ³⁴.

[Page 26, Line 425-426]

The spatial differences and covariation patterns of thresholds are shaped by gradient differences in **heat and moisture conditions**, vegetation productivity, and human activities (Fig. 3).

Comment 3: Lines 128-129 – Monthly fire weather index (FWI) data can only weakly correlate to the actual wildfires unless the fires persist for the whole month. It certainly doesn’t “assess the impact of weather conditions on wildfires”. I can see the attraction for using the data but they are more of a fire season indicator than fire weather when averaged over a month of day/night, rain/shine, cool/hot conditions. FWI is conceived of as a daily indicator of potential fire intensity. If used, this has to be more clearly indicated as being averaged monthly FWI or termed something like average seasonal intensity.

[Page 7, Line 128-129]

A public monthly fire weather index (FWI) dataset from 2002 to 2020 developed from the ERA5 reanalysis dataset was also employed to assess the impact of weather conditions on wildfires³³.

Response 3: Thank you for pointing out this issue. We concur that using the monthly Fire Weather Index (FWI) to assess weather conditions and their impact on wildfires is inappropriate.

- (1) We have revised this sentence to specify that the dataset used is the "averaged monthly FWI," as you suggested.
- (2) The purpose of using this dataset has been clarified: it serves to provide a climatic indicator for characterizing potential fire risk over extended periods.
- (3) In this study, the average monthly FWI was further aggregated within the fire season to calculate FWI_FS, an average seasonal indicator that aligns with your expectations. Additionally, we revised another sentence to clarify the calculation methods for FWI_FS and other variables.

[Page 8, Line 133-135]

A public **averaged monthly fire weather index (FWI) dataset** from 2002 to 2020, developed from the ERA5 reanalysis dataset, was also employed to obtain a climatic indicator characterizing potential fire risk³⁵.

[Page 10, Line 183-185]

We used the BA during fire season (BA_FS) as the target variable. Mean temperature (Tem_FS), total precipitation (Pre_FS), **average monthly FWI (FWI_FS)**, and vapor pressure deficit (VPD_FS) were each aggregated as seasonal explanatory variables to characterize the climatic conditions during the fire season.

Comment 4: Line 137 – shouldn't the land cover change (LCC) data extend to 2022, not end at 2021?

[Page 7, Line 137-138]

A 0.25° LCC dataset from 2002 to 2021 was subsequently constructed to quantify the magnitude of land cover change.

Response 4: Thank you for your comment. The LCC dataset used in our study is derived from the Plant Functional Types dataset (MODIS MCD12Q1), which provides data only up to 2021 at the time of this study. The land cover change (LCC) data did end at 2021, but we used the LCC of 2021 as the LCC of 2022 due to data limitations. We believe that this limitation does not compromise the validity of our results, as this analysis is conducted based on multiyear averages of wildfire drivers and LCC has very limited variation in adjacent years. We have revised this sentence as you suggested to clarify the procedure for handling missing values, and hope that it is now clearer.

[Page 8, Line 142-144]

A 0.25° LCC dataset from 2002 to 2021 was subsequently constructed to quantify the magnitude of land cover change, in which the LCC of 2022 was substituted with the LCC of 2021, as the latest PFT dataset is only updated to 2021.

Comment 5: Lines 140-141 – How were 2020-2022 dealt with for the missing GDP data?

[Page 7, Line 140-141]

We also used a global 1-km gridded revised real gross domestic product from 2001 to 2019³⁸.

Response 5: We sincerely appreciate your careful review. It was our oversight not to specify the interpolation process for the GDP data. We have revised this sentence and clarified the interpolation process. While missing data and interpolation may introduce some uncertainty, we believe this does not undermine the validity of our results, as we use multiyear GDP averages for our modeling and analysis.

[Page 8, Line 146-149]

We also used a global 1-km gridded revised real gross domestic product from 2001 to 2019 and extended this dataset to 2022⁴⁰. Specifically, we developed a simple linear regression model using available time series data at the pixel scale and interpolated GDP values from 2020 to 2022 based on the model parameters obtained.

Comment 6: Lines 165-166 – Are these averaged fire seasons for the 2001-2022 time period or are the fire seasons independently variable by year? Beyond variability, the seasons presumably have been extending over time during the study period as well and certainly will in the future climate scenarios.

[Page 9, Line 165-166]

We ultimately calculated the multiyear average BA for each calendar month to identify the fire year and its fire-prone months, thereby extracting fire seasons (Fig. S2).

Response 6: Thank you for this insightful comment. To address your concerns, we further refined the interpretation of the fire season extraction method and revised the sentence to clarify the stability of fire seasons under future climate scenarios.

- (1) The fire year, fire-prone months, and fire season were extracted based on the multiyear average burned area (BA) for each of the 12 calendar months from 2001 to 2022.
- (2) We acknowledge that fire seasons may extend under future climate scenarios. Although our current analysis does not explicitly explore future fire season changes, we accounted for this possibility when defining the fire season. Specifically, we used an 80% burned area threshold, as opposed to a stricter 90%, to ensure that the fire season encompasses a broader period and remains relatively stable in the future, even if slight changes occur.
- (3) We assumed that the fire season would remain constant in the future. This approach mitigates the impact of fire season variability on projections and comparisons of burned areas, while also help to determine the role of threshold effects in wildfire changes.

[Page 10, Line 178-182]

We ultimately calculated the multiyear average BA for each of the 12 calendar months from 2001 to 2022 to identify the fire year and fire-prone months at the pixel scale, thereby extracting a broad and stable fire season for each grid cell (Fig. S2). We assumed that the fire season would remain constant in the future. This assumption reduces the influence of fire season variability on BA projections and comparisons, thereby facilitating the identification of threshold effects in wildfire changes.

Comment 7: Lines 177-178 – Were the training/testing/validation data randomly placed by pixel or spatially stratified in some other way?

[Page 10, Line 177-179]

We converted historical multiyear averages (2001–2022) to a modeling dataset and randomly divided it into training, testing, and validation sets at a ratio of 6:2:2.

Response 7: Yes, the training/testing/validation datasets were only randomly divided by pixels without spatial stratified sampling. However, when fitting the threshold regression model and the XGBoost model, we applied stratified bootstrap sampling to mitigate the spatial autocorrelation and balance the samples (**Page 11, Lines 202-204**). We adjusted the order of the validation and testing sets to match the presentation specification.

[Page 10-11, Line 194-195]

We converted historical multiyear averages (2001–2022) to a modeling dataset and randomly divided it into training, validation, and testing sets at a ratio of 6:2:2.

Comment 8: Lines 205-206 – It is not clear how the Pearson’s correlation coefficients were used to explore “analogous spatial patterns”. Were correlations between all variables examined at a 0.25° scale or as classes?

[Page 11, Line 204-206]

Specifically, Pearson's correlation coefficients were calculated between thresholds of different drivers to explore their analogous spatial patterns.

Response 8: Thank you for your insightful comment.

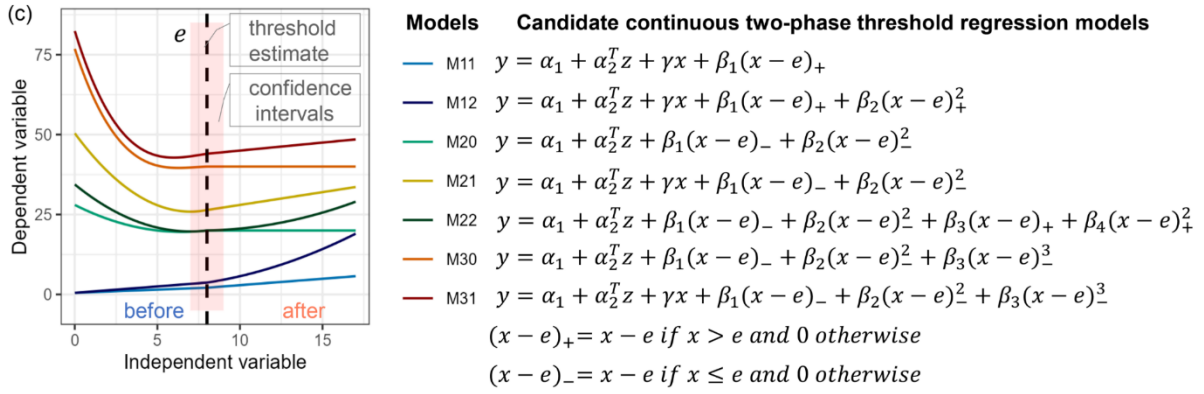
- (1) We have refined our description of using Pearson's correlation coefficients to explore “analogous spatial patterns” and hope that it is now clearer. To clarify, Pearson's correlation coefficients were calculated between the thresholds (or threshold effects) of different drivers at the ecoregion scale. We have revised this sentence to include this clarification.
- (2) The correlation coefficients between all variables examined at the ecoregion scale.

[Page 12, Line 222-225]

Specifically, Pearson's correlation coefficients were calculated to examine the relationships between thresholds (or threshold effects) of different drivers **at the ecoregion scale**. Significant correlations indicated that these thresholds (or their threshold effects) exhibited analogous spatial patterns across ecoregions.

Comment 9: Figure 1 panel c – Why is e (dashed line) set at ~8 for all cases?

[Page 12, Line 212, Figure1 c]



(c) Candidate threshold regression models, where e is the threshold parameter, x is the predictor with threshold effects, and z is a vector of additional predictors.

Response 9: We would like to clarify that Figure 1 panel c is a conceptual illustration designed to explain the principle of threshold regression models. The e (dashed line) at ~ 8 is a hypothetical representation of the threshold parameter for demonstration purposes only. It does not refer to any initial values or the estimated parameters in our actual modeling. To avoid confusion, we have revised the figure caption to clarify this point and ensured that the conceptual nature of the illustration is explicitly stated.

[Page 13, Line 236-237]

Any parameters in this panel are hypothetical representations of the threshold regression model and are not related to the initial values.

Comment 10: Figure 2 – How is this interpreted? I am confused especially by Pop and LCC. What is signified by STMS Pop (j) which has a threshold effect that is substantially below the average e (i.e. blue line), but has a strong enhancing threshold effect (red with cross in the circle), however it is located at a negative value on the x axis? Please explain. Why is e average set to the top of the regional average range in all cases? Is there any way to derive the net effect of all the drivers for an ecoregion (e.g. polar)? Are they additive? Note too that FWI is mostly a weakening effect because it is actually a monthly average not a true FWI comparison.

[Page 15, Line 270, Figure 1]

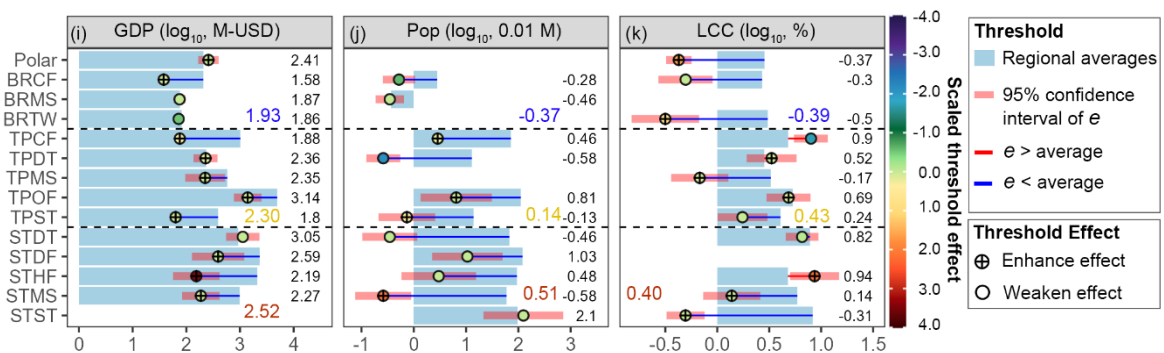


Fig. 1. Thresholds and threshold effects of wildfire drivers at ecoregion scales. The blue bars are the average of wildfire drivers in each ecoregion, facilitating comparisons with thresholds. The positions of colored dots

on the x-axis are the thresholds of wildfire drivers with text labels on the right side. The color scale of the dots is the strength and direction of the threshold effects (z-score scaled). The blue, yellow, and red fonts are the averages of thresholds in the polar and boreal, temperate, and subtropical ecoregions, respectively.

Response 10: Thank you for your insightful comments and constructive feedback. We divided your comment into five questions and explained or answered each one in turn. We hope these explanations can clear your confusion and meet with your approval.

(1) How is this interpreted?

The figure caption has explained the specific meanings of each element in Figure 2. Here, we use the STMS and STDT in Figure 2 (i) as examples to interpret the threshold and threshold effects of GDP. We hope these explanations help you fully understand the information presented in Figure 2.

- In Figure 2 (i), the unit of GDP is million USD and the values are log10 transformed. The GDP threshold in STMS is 2.27, and when GDP exceeds this threshold, a positive threshold effect emerges, which enhances the impact of GDP on wildfires. Currently, the regional average (blue bar) of GDP in STMS is around 3, well above the threshold (blue line), and has shown a positive threshold effect (red with a cross in the circle), which enhanced the changes in wildfires.
- In contrast, the GDP threshold in STDT is 3.05, and when GDP exceeds this threshold, a negative threshold effect emerges, which weakens the impact of GDP on wildfires. However, the current regional average GDP does not reach the threshold, nor does it have a negative impact or weaken the change on wildfires.

(2) I am confused especially by Pop and LCC. What is signified by STMS Pop (j) which has a threshold effect that is substantially below the average e (i.e. blue line), but has a strong enhancing threshold effect (red with cross in the circle), however it is located at a negative value on the x axis? Please explain.

We have added a note about negative values in the figure caption and would like to explain this phenomenon from two aspects:

- We have to state that GDP, Pop, and LCC have been log10-transformed, as described in the Method section (**Page 10, Lines 191-193**), to mitigate skewness and normalize the data range. Thus, the decimals in the original Pop (unit: 0.01 million people/0.25°grid) and LCC (unit: %) data lead to negative values after logarithmic transformation, potentially resulting in negative thresholds.
- This phenomenon is also interpretable. For instance, the Pop threshold in STMS is -0.58 (negative value on the x-axis). When Pop exceeds this value, a positive threshold effect emerges (red with a cross in the circle), which enhances its impact on wildfires. Currently, the regional average Pop significantly exceeds the threshold in STMS (blue line), exhibiting a positive threshold effect that exponentially enhances wildfire dynamics. This phenomenon suggests that population dynamics are dramatically promoting wildfires in subtropical montane systems.

[Page16, Line 293-295]

Note: The original values of Pop and LCC include decimals, resulting in negative values after logarithmic transformation.

(3) Why is the average set to the top of the regional average range in all cases?

- The threshold in this study refers to the point where the interaction between wildfires and their drivers shifts. We have to clarify that no initial value was deliberately set near the regional average during the threshold identification process.
- The relative position of the threshold to the regional average is primarily influenced by the skewness of the bivariate distribution between wildfires and drivers. For example, if the distribution is normal, the threshold is close to the average; if negatively skewed, the threshold is below the average; and if positively skewed, the threshold is above the average. Therefore, the relative position of the threshold to the regional average serves as a tool to investigate their nonlinear properties, which form the basis of this study.

(4) Is there any way to derive the net effect of all the drivers for an ecoregion (e.g. polar)? Are they additive?

- Yes, there are ways to accomplish this, which is what the **3.2 Section** addresses and is one of the innovations of this paper. We quantified threshold effects by incorporating threshold parameters in a multifactor interaction model and thus calculated the actual net effects of drivers and their threshold effects on wildfire for each ecoregion using Shapley contribution analysis.
- No, the net effect on wildfires cannot be calculated simply by summing the threshold effects, because there are complex interactions between both the drivers and their threshold effects. In addition, the units of wildfire drivers are different and cannot be added directly and linearly.

(5) Note too that FWI is mostly a weakening effect because it is actually a monthly average not a true FWI comparison.

- Thank you again for your kind reminder. We fully agree with you that monthly average FWI is not a true FWI comparison. As per your suggestion in **Comment 3**, we have clarified that we used FWI_FS, which is a seasonal average indicator.
- We also acknowledge that the linear relationships between FWI_FS and wildfires, as well as the weakening threshold effects, may result from using the average seasonal FWI (FWI_FS). However, we also believe that these weakening threshold effects largely depend on the properties of the FWI_FS itself and the wildfire-vegetation productivity-drought relationships. Specifically, the relationship between wildfires and FWI_FS typically follows a hump-shaped curve (*Fig.R2 a*). When FWI_FS exceeds a certain threshold, its impact diminishes, resulting in a weakening threshold effect (*Fig.R2 b*). This is because the wildfire-FWI_FS relationship may also influence by vegetation productivity, and extreme arid environments often suppress wildfire occurrence due to severe fuel limitations (*Fig. R2.c*).

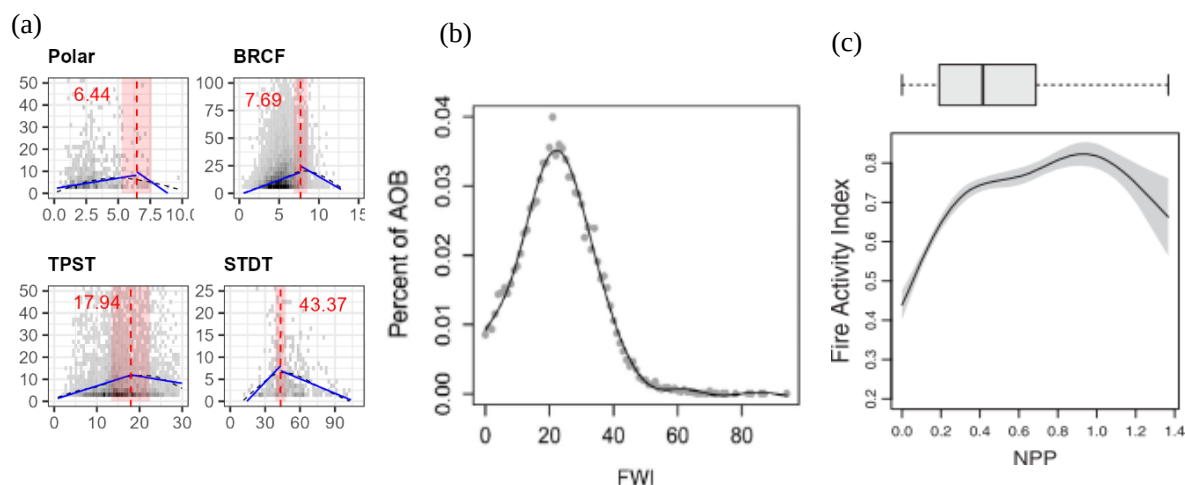


Fig.R2. (a) The nonlinear threshold relationships between BA_FS and FWI_FS in this study. (b) The proportion of total area burned by each unit FWI System variables summarized over the study area (Wang et al., 2023). (c) Generalized additive model (GAM) fit of the fire activity index against net primary productivity (NPP) (Pausas et al., 2013).

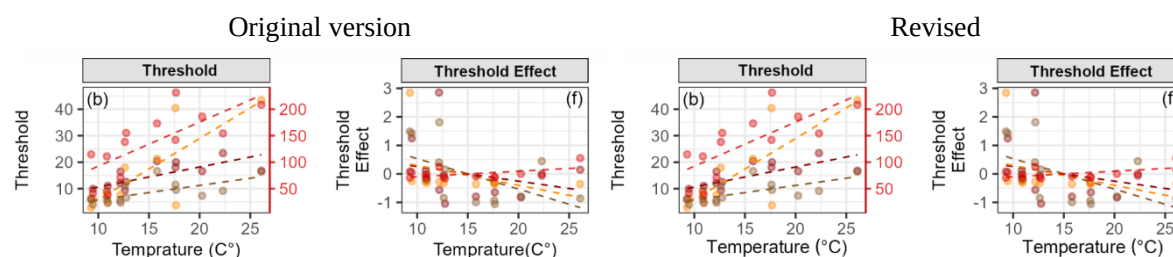
References

- [1] Wang X., Oliver J., Swystun T., Hanes C.C., Erni S., Flannigan M.D., 2023. Critical fire weather conditions during active fire spread days in Canada. 869, 161831. <https://doi.org/10.1016/j.scitotenv.2023.161831>.
- [2] Pausas J.G., Ribeiro E., 2013. The global fire-productivity relationship. Glob. Ecol. Biogeogr. 22, 728–736. <https://doi.org/10.1111/geb.12043>.

Comment 11: Figure 3 – need to correct the spelling of Temperature in panels b and f.

Response 11: We appreciate your careful review and bringing this to our attention. The spelling of "Temperature" and unit in panels b and f of Figure 3 has been corrected. The revised figure is now included in the updated manuscript.

[Page 18, Line 311]



Comment 12: Lines 303-305 – Instead of just saying that all these regions had threshold effects >30.37% provide the values in parentheses after each region name so the reader can see if the differences are marginal or substantial. Likewise, do the same for lines 304-305, provide the values for the regions below 28.39%.

[Page 18, Line 303-305]

Threshold effects had greater contributions (>30.37%) to BA in steppes and deserts in temperate and

subtropical regions and boreal coniferous forests, but lower contributions (<28.39%) to BA in temperate coniferous forests, subtropical humid and dry forests, and mountain systems (Fig. 4, Fig. 5 a, b).

Response 12: Thank you for your valuable suggestion. We have revised the text to include the specific values for each region in parentheses, which provides a clearer comparison of the contribution ratio among different regions.

[Page 19, Line 324-327]

Threshold effects had greater contributions to BA in subtropical steppes (33.05%) and deserts (30.37%), temperate steppes (34.90%) and deserts (34.40%), and boreal coniferous forests (30.45%), but lower contributions to BA in temperate coniferous forests (25.94%), subtropical humid and dry forests (27.13% and 17.93%), and boreal mountain systems (25.65%) (Fig. 4; Fig. 5 a, b).

Comment 13: Lines 318-320 – What does it mean to dominate wildfires? I assume that you mean that it is the strongest explanatory variable...

[Page 19, Line 318-320]

Precipitation explained 25.28% of the BA changes and dominated wildfires in 56.63% of the land areas, including desert, steppes, and mountain systems in temperate and subtropical regions (Fig. 5 c).

Response 13: We appreciate this valuable and constructive feedback. We recognize that the term “dominate” may cause ambiguity in these sentences.

- (1) To enhance clarity, we used “the strongest explanatory variable of wildfires” as you suggested, and revised all relevant sentences. Additionally, the area fraction was adjusted from 56.63% to 23.26%, and specific reasons will be explained in **Response 16**.
- (2) We also revised the legend title of Figure 5, replacing “Most important driver” with “Strongest Explanatory Variable” and “Most important TE” with “Strongest Explanatory TE”.

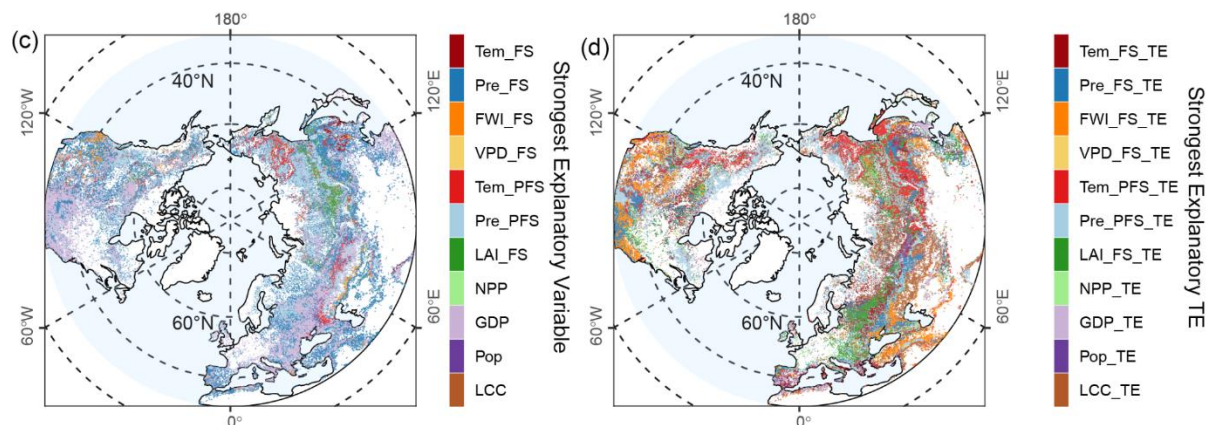
[Page 14, Line 251-252]

The strongest explanatory variable and key threshold effects across ecoregions were also identified to analyze their spatial heterogeneity.

[Page 20, Line 341-343]

Precipitation explained 25.28% of the BA changes and served as the strongest explanatory variable of wildfires in 23.26% of the land areas (Table. S7), including deserts, steppes, and mountain systems in temperate and subtropical regions (Fig. 5 c).

[Page 21, Line 357]



Comment 14: Lines 321-324 – Dominated again. FWI should make clear this is a monthly average or have a revised name. Misleading as presented.

[Page 18, Line 321-324]

In contrast, temperature and FWI explained only 8.82% and 6.21% of the BA changes and dominated wildfires in 3.81% and 4.41% of the areas, mainly in the mountain systems of eastern Siberia and North America and the temperate coniferous forests of East Asia.

Response 14: Thank you for pointing out these issues again. We have revised this sentence in two aspects and used a revised name of the monthly averaged FWI during the fire season (FWI_FS).

- (1) We have replaced the phrase "dominated wildfires" with "were the strongest explanatory variable of wildfires" to more accurately reflect their role in explaining wildfire variability. We believe this revision enhances the precision and clarity of this sentence.
- (2) As you pointed out, the direct use of the term "FWI" could lead to conceptual confusion. We have revised the abbreviation to "FWI_FS", which specifically refers to the monthly average FWI during the fire season. The term "FWI_FS" was defined earlier in the manuscript (**Page 10, Line 184**) and used continuously throughout the text. We hope that this revision enhances clarity and meets your expectations.
- (3) The area fractions were also modified from "3.81% and 4.41%" to "2.24% and 1.24%", respectively, for the reason given in **Response 16**.

[Page 20, Line 345-348]

In contrast, temperature and FWI_FS explained only 8.82% and 6.21% of the BA changes during the fire season, respectively. They were the strongest explanatory variable of wildfires in 2.24% and 1.24% of the land areas, respectively, mainly in the mountain systems of eastern Siberia and North America and the temperate coniferous forests of East Asia.

Comment 15: Lines 324-325 – "controlled wildfires" – what does that mean? Does ~29% signify control? Weren't the drivers more important? These were certainly substantial contributors but not the main ones.

[Page 19, Line 324-325]

Moreover, the threshold effects of precipitation, temperature, LCC, and LAI collectively explained 19.87%

of the BA changes and controlled wildfires in 77.4% of the land areas (Fig. 4, Fig. 5d).

Response 15: We apologize for this unclear interpretation. To address your concern, we have revised the sentence for clarity.

- (1) The area fractions were also modified from 77.4% to 23.68% for the reason given in **Response 16**.
- (2) We intended to convey that the threshold effects of these drivers were the strongest explanatory variable of wildfires in 23.68% of land areas, excluding the main contribution of the drivers. As you pointed out, the term "controlled wildfires" may confuse, so we have removed it to eliminate ambiguity.
- (3) We also fully agree that the dominant role of the drivers should be excluded when describing the ordering of the contribution of threshold effects, to avoid confusing primary and secondary relationships. Therefore, we have added such clarifications to enhance the rigor of the presentation.

[Page 20, Line 348-351]

Moreover, the threshold effects of precipitation, temperature, LCC, and LAI_FS collectively explained 19.87% of the BA changes (Fig. 4; Fig. 5d). They were the strongest explanatory variables of wildfires in 23.68% of land areas when excluding the main contribution of the drivers and focusing only on threshold effects.

Comment 16: Figure 5 – FWI_FS_TE looks to be much more important among threshold effects in this figure than would seem warranted in figure 4. Conversely Pre_FS_TE looks much less important here than in figure 4. What is the explanation?

Response 16: Thank you for pointing this out. We used the statistics in Table.R1 to address your concern and justify our results. We hope these explanations and revisions meet with your approval.

- (1) The discrepancy you noted may arise from the different metrics presented in Figures 4 and 5. Figure 4 shows the average contribution of each feature across all samples, while Figure 5 depicts regional differences and the area fractions of the strongest explanatory variable among threshold effects. As shown in Table R1, the area fraction where Pre_FS_TE is the strongest explanatory variable is actually larger than the fraction where FWI_FS_TE is strongest in Figure 5 ($4.35\% > 3.28\%$).
- (2) Based on the above prerequisites, Pre_FS_TE contributes significantly more to a single sample (3.65%) compared to FWI_FS_TE (2.39%) in Figure 4, which leads to it being the strongest explanatory variable in more regions of Figure 5. Conversely, FWI_FS_TE contributes less to a single sample in Figure 4, which leads to it being the strongest explanatory variable in relatively fewer regions of Figure 5. Thus, despite the different metrics presented in Figures 4 and 5, their results are consistent and mutually supportive.
- (3) We acknowledge that the absence of statistical data to support the results in Figure 5 may lead to confusion for readers. Additionally, we identified an inconsistency in the area calculation method between this section and the rest of the manuscript. Therefore, we have recalculated the area fractions based on the whole land area of mid-high latitudes, updated the manuscript accordingly, and included a complete table (Table.S7) in the supplementary materials for clarity.

Table R1. Summary of area fraction and contribution of features

Features	Count	Area Fraction (%)	Mean Contribution (%)
Tem_FS_TE	5993	3.82	2.73
Pre_FS_TE	6824	4.35	3.65
FWI_FS_TE	5141	3.28	2.39
VPD_FS_TE	918	0.59	1.72

[supplementary materials, Table.S7, Page 17, Lines 143-146]

Please kindly refer to Table.S7 in the supplementary materials.

[Page 20, Lines 343-344]

The GDP explained 13.07% of the BA changes, significantly affecting wildfires in 13.03% of the land areas, especially around human settlements.

[Page 20, Lines 351-353]

The threshold effects of precipitation contributed more to wildfires than those of temperature (8.26% > 5.43%) and covered broader areas than the threshold effects of temperature (13.77% > 8.64%).

Comment 17: Lines 407-410 – Can you provide an example from the results to illustrate this phenomenon or that supports this contention?

[Page 26, Line 407-410]

More importantly, correlations and covariation patterns among thresholds also suggest that changes in individual drivers may trigger ripple effects of wildfire responses, causing successive exceedances of interconnected thresholds⁵⁴ and obscuring the impact of threshold effects of individual drivers^{54, 55}.

Response 17: We appreciate this thought-provoking suggestion. We realized that this long sentence is difficult to understand. In response to your comment, this sentence has been split into two sentences with separate examples.

[Page 27, Line 434-443]

More importantly, correlations and covariation patterns among thresholds also suggest that changes in individual drivers may trigger ripple effects of wildfire responses, causing successive exceedances of interconnected thresholds⁵⁶. For example, higher temperatures increased both VPD_FS and pre-season temperature, sequentially triggering their thresholds, as these thresholds are positively correlated and jointly driven by heat variability (Fig.3 a–b). Moreover, their threshold effects may interact with each other to obscure the spatial pattern of threshold effects of individual drivers^{56, 57}. For example, the negative threshold effects of VPD_FS and pre-season temperature partially counterbalance the positive threshold effects of temperature in boreal and polar ecosystems (Fig.2 a, d, e). Consequently, their threshold effects fail to exhibit significant spatial patterns along the heat gradient (Table. S6).

Comment 18: Lines 431-433 – “reduce the overall increase drop” – not clear what that is supposed to mean. Also, the results seem to show considerable variance in the scenario responses with some areas having

reduced BA for higher emission scenarios. Some nuance to the description as compared to overall regional averages is warranted.

[Page 27, Line 431-433]

Importantly, our results highlighted that lower emission scenarios can significantly mitigate the long-term increasing trend in wildfires and reduce the overall increase drop to at least 41% by the end of this century, which is lower than high emissions scenarios (>55%) (Fig. 6 g–i).

Response 18: Thank you for your insightful comments and constructive feedback, which have significantly enhanced our discussion and expanded our perspective.

- (1) We agree that the phrase “reduce the overall increase drop” was unclear. This sentence has been revised to convey that lower emission scenarios help keep the increase in future burned areas to 41%.
- (2) As per your suggestion, we further discussed the overall increase in burned areas under higher emission scenarios and how the ongoing decline in burned areas in key regions influences overall wildfire trends.

[Page 28, Line 464-469]

Importantly, our results highlight that lower emission scenarios can significantly mitigate the long-term increasing trend in wildfires, keeping the overall increase in burned areas to 41% by the end of this century (Fig. 6 g–i). Comparatively, the overall increase in burned areas will exceed 55% under higher emission scenarios, posing a significant threat to boreal ecosystems in particular. In this context, although the burned areas in temperate steppes are expected to continually decrease due to enhanced human control measures (Fig. 6 a–f), the mitigating effect on the overall increase in wildfires will be rather limited.

Comment 19: Lines 439-440 – Somewhat misleading to state it in this way since all <30°N land area for the hemisphere is not included and the tropics have more burned area than either the boreal or temperate regions.

[Page 27, Line 439-440]

Temperate and boreal ecosystems, accounting for more than 80% of wildfires (Fig. S2 d), are more sensitive to climate change and susceptible to threshold effects.

Response 19: Thank you for your valuable feedback and this interpretation is misleading. We have added geographical limitations to ensure accuracy.

[Page 29, Line 475-477]

Wildfires in temperate and boreal ecosystems contribute to more than 80% of burned areas at mid–high northern latitudes and are more sensitive to climate change and susceptible to threshold effects (Fig. S2 d).

Comment 20: Lines 456-459 – Ok, stated well but why is there no consideration that additional thresholds may exist that were not reached in the early 21st century but could be in the coming decades under the climate change scenarios? Surely it is not presumed that all possible thresholds have been discovered in this work based on climate change experienced to date?

[Page 28, Line 456-459]

Second, we used thresholds obtained from the early 21st century and assumed their robustness in the future. However, ecosystem adaptation to climate changes, vegetation feedback, and shifts in human development

concepts may alter these threshold parameters, introducing nonstationarity into the established relationships
4, 67, 68

Response 20: We sincerely thank you for this valuable comment. Your unique perspective is greatly appreciated and has significantly enriched our thinking and discussion.

- (1) We fully agree with you that additional thresholds may exist that were not reached or identified in the early 21st century but could be in the coming decades under the climate change scenarios. For example, wildfires currently exhibit a linear response to some drivers, which may transition to a nonlinear relationship and exhibit threshold effects in the future. With this in mind, we have refined our discussion of limitations and hope it meets your expectations.
- (2) Moreover, there are indeed cases where wildfire drivers do not reach the thresholds in the early 21st century, but may exceed these thresholds in the future. Our model can handle such cases by incorporating $(x - e)_+$ and $(x - e)_-$, which have been defined in Fig.1 c. If x exceeds the threshold (e) in the future, these parameters may take effect, thus showing threshold effects.
- (3) We also acknowledge that it is unrealistic to cover all potential driving factors and identify their thresholds in this work. Given the data and model limitations, this study only focuses on analyzing and quantifying the major wildfire drivers. Research on additional drivers exhibiting threshold effects will be conducted in the future.

[Page 30, Line 497-498]

Meanwhile, such changes may also potentially trigger additional drivers of otherwise linear changes to exhibit nonlinearity and threshold effects in the future, complicating the identified multifactor interactions.

Comment 21: Lines 466-467 – Geographical differences such as what? The only element that was described was latitude.

[Page 28-29, Line 466-468]

Our findings suggest that the geographical difference in thresholds effectively explains spatial patterns of the wildfires and their uneven responses, and the threshold effects of drivers overall contribute to roughly one-third of wildfire variability at mid–high northern latitudes.

Response 21: Geographical differences mentioned in this study include: ecological and climatic zones (Figure 2), latitude (Fig.S4-S5), and gradients of environmental factors (heat, humidity, vegetation productivity, and human activities) (Fig.3 b-j). Consequently, in the conclusion section, we used “geographic differences” to summarize the differences in thresholds or threshold effects across these geographical areas.

Comment 22: Figure S1 – Why are there 2-8 models used for each panel but 6 are used in the main text?

Response 22: Thank you for your comment. We would like to explain and justify the rationale for CMIP 6 model selection. Figure S1 illustrates the basic process of selecting CMIP6 climate models based on their performance in fitting historical data. Take Figure S1 (b) as an example, while seven models achieved the required temporal and spatial resolutions to generate precipitation data, the EC-Earth3-Veg model provided the best agreement with historical observations. Therefore, this model was selected for further analysis and

the remaining models were not considered. After evaluating all candidate models for 6 basic variables, we selected only one model for each variable that is most suitable for our study. Finally, these selected models (6 models) will be used to project future wildfires in the main text.

Comment 23: Supplement Line 80 – “donates” should probably be ‘denotes’.

[Supplementary Materials, Page 6, Line 81-82]

The red line donates the mean value of BA.

Response 23: Thank you for your careful check and we have corrected "donates" to "denotes".

[Supplementary Materials, Page 6, Line 81-82]

The red line **denotes** the mean value of BA.

Comment 24: Supplement Lines 99-101 – since more pairwise relationships weakened the BA than strengthened it, what is the reason for the net increase in BA. Is this caused by the magnitudes of the relative weakening and strengthening relationships and/or the respective areas of relevant ecoregions where the net effect was to increase/decrease BA?

[Supplementary Materials, Page 16, Line 99-101]

The results showed that 66 pairwise relationships between BA and wildfire drivers were enhanced once their thresholds were exceeded, whereas 76 pairwise relationships were weakened.

Response 24: We sincerely appreciate your professional comments and insightful perspective. Yes, the relative weakening and strengthening of relationships and the interaction among threshold effects of different wildfire drivers are one of the main causes. Here we have added two other explanations to further address your concern and hope these interpretations meet your approval.

- (1) It is crucial to clarify that a negative threshold effect implies diminished wildfire-driver relationships, but this does not necessarily lead to a reduction in BA. Take Fig.R3 as an example, increasing drought leads to a significant increase in BA, and once a certain drought threshold is surpassed, the negative threshold effect emerges. Although the negative threshold effect weakens the wildfire-driver relationships, a severe drought continues to drive a sustained increase in BA, albeit at a reduced increasing rate.
- (2) Interactions and offsets between drivers and threshold effects are even more significant than those between threshold effects themselves. If changes in the drivers themselves predominantly result in increasing BA, a negative threshold effect, although present, may not be sufficient to fully counteract the impact of the driver thus preventing a significant net reduction in BA. This argument is consistent with our finding that the contribution ratio of the driver and threshold effects is 7:3, suggesting that the role of threshold effects, while important, is still limited in terms of offsetting or promoting effect.

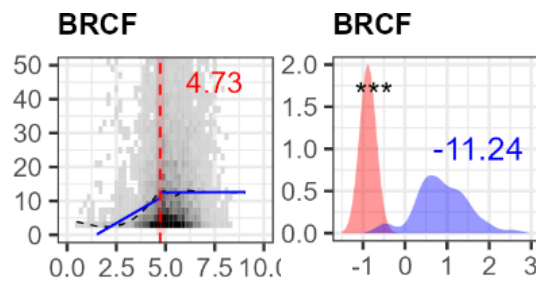


Fig.R3. The threshold and negative threshold effect of VPD (excerpted from Table.S4 and Table.S5)

Comment 25: Supplement Lines 136-141 – threshold addition improved BA explanatory power by 1.6% and test RMSE by 0.23. The text states that this significantly improved interpretability but was there any actual test for significance? The results are improved but not tremendously.

[Supplementary Materials, Page 16, Line 141-142]

Therefore, considering threshold parameters significantly improved the interpretability and fitting accuracy of the model for BA.

Response 25: Thank you for your comment regarding the use of the term “significantly”.

- (1) We state that no formal significance testing is performed when comparing the models. This is because RMSE is a widely used measure of model fit and prediction error, allowing models to be compared directly based on RMSE values.
- (2) Moreover, the bootstrap method was applied in model fitting and validity estimation to calculate the RMSE for model comparison. Bootstrap methods are more robust than traditional parametric tests in spatial data modeling, as spatial autocorrelation may violate the assumption of independence required for parametric tests. Therefore, we believe that the results of the current model comparison based on Bootstrap are adequate and valid.
- (3) We fully agree with you that the use of “significantly” may also overstate the results. Therefore, this word has been removed from this sentence.

[Supplementary Materials, Page 16, Line 141-142]

Therefore, considering threshold parameters improved the interpretability and fitting accuracy of the model for BA.

Response to Reviewer #2 Comments

Reviewer #2:

“Enhanced Threshold Effects of Drivers Promote Future Wildfire Changes at Mid-High Northern Latitudes” presents a comprehensive analysis of the threshold effects of various climate and population variables on the effects of burned area across mid-high northern latitude ranges, as well as making broad forecasts of potential fire activity using these threshold effects to the end of the century. Overall, the content of the paper and its methodology is sound, the paper follows a logical structure, the results are backed up with reasoning and all the figures and tables are relevant. Commentary is supported by a good number of references and soundly follows from the results. The statistical analysis is comprehensive; several variables and tests are used to ensure the validity of the investigation, and the process is well documented either in the main body of the text or in the supporting material to ensure the work is reproducible. The findings are novel, relevant, and important for future work. There are no issues with the English language. I have a handful of very minor comments and suggestions and, if these are dealt with, I would recommend subsequent publication.

Response to reviewer 2 comments:

We sincerely appreciate your positive evaluation of our manuscript and the time you dedicated to providing valuable comments and suggestions. We are also pleased to learn that you found our work novel and important to future research in this field. Your encouraging feedback on the quality of our analysis and writing is also greatly appreciated. In this revision, we have carefully addressed all your minor comments and suggestions to further improve the manuscript. We also invited four non-expert readers to review the manuscript and revised some potentially unclear sentences. Their feedback was incorporated to enhance the manuscript’s overall clarity and coherence. Below, we provide point-by-point responses to your comments. Each response includes: your comment (in red), the original text (in black), our response (in blue), and the revised text or figures (in black) with corresponding page and line numbers. Additionally, we also provided a separate document with tracked changes (red text), using cyan highlighter to mark all modifications made based on your comments. We hope that our responses and the revised manuscript meet your expectations. Thank you once again for your invaluable feedback and your recommendation for publication.

Minor comments:

Comment 1: L. 116 – you extend the BA time series for 2021 and 2022 using MCD64A1 (and other products) “via methodologies similar to those used by the dataset producers”. In Eurasia especially, MCD64A1 has been found to significantly underestimate FireCCI51 (see Clelland et al., Annual and Seasonal Patterns of Burned Area Products in Arctic-Boreal North America and Russia for 2001-2020, Remote Sensing, 2024, 16(17), 3306). As such these two years could underestimate the total BA. I would either state this as a limitation, or provide more evidence that your extension is a reliable continuation of the previous FireCCI51 dataset, as the current explanation seems vague.

[Page 7, Line 115-116]

Since the Fire CCI51 dataset is updated only to 2020, we extended the BA time series to 2022 via methodologies similar to those used by the dataset producers.

Response 1: Thank you for your constructive feedback. We acknowledge that MCD64A1 has been found to underestimate the total burned area, particularly for crop fires and small burned areas in Eurasia. To address your concerns, we have made the following explanations and revisions:

- (1) Since the FireCCI51 dataset was last updated in 2020, and the specific production algorithms are not disclosed, we were unable to directly assess the consistency between the extended dataset and the original FireCCI51. However, since FireCCI51 is based on MCD64A1, previous studies, such as those by Joshua et al., have shown consistent spatial and temporal patterns between these two datasets for burned areas. This suggests that although discrepancies exist between the datasets, their impact on the overall analysis of spatial and temporal patterns is limited.
- (2) We used multi-year averages of burned areas in our analysis to further mitigate the potential underestimation of burned areas for 2021 and 2022, which may help smooth out some year-specific anomalies.
- (3) As per your suggestion, we stated this as a limitation when describing the BA dataset. We also refined the interpretation by citing two references to justify the reliability of the analysis despite these potential discrepancies. We hope these revisions clarify our methodology and address the concerns raised.

[Page 7, Line 120-124]

Notably, although BA has high spatiotemporal consistency between the MCD64A1 and FireCCI51 datasets³¹, our extended method may underestimate BA in both years. This is because FireCCI51 uses an updated BA detection algorithm that is more sensitive to small fires, thus reducing BA underestimation²⁸. However, since multiyear average BA was finally used for analysis, the potential impact of this discrepancy on our results is relatively limited.

References

- [1] Clelland A.A., Marshall G.J., Baxter R., Potter S., Talucci A.C., Rady J.M., et al., 2024. Annual and Seasonal Patterns of Burned Area Products in Arctic-Boreal North America and Russia for 2001–2020. 16. <https://doi.org/10.3390/rs16173306>.

- [2] Lizundia-Loiola J., Otón G., Ramo R., Chuvieco E., 2020. A spatio-temporal active-fire clustering approach for global burned area mapping at 250 m from MODIS data. 236. <https://doi.org/10.1016/j.rse.2019.111493>.

Comment 2: L. 165 – you “calculated the multiyear average BA for each calendar month” – is this for each grid cell and/or ecoregion? It’s not quite clear.

[Page 9, Line 165-166]

We ultimately calculated the multiyear average BA for each calendar month to identify the fire year and its fire-prone months, thereby extracting fire seasons (Fig. S2).

Response 2: Thank you for your question regarding our analysis scale. We calculated the multiyear average BA for each calendar month at the pixel scale. We have revised this sentence to specify the analysis scale and refine the interpretation.

[Page 10, Line 178-180]

We ultimately calculated the multiyear average BA for each of the 12 calendar months from 2001 to 2022 to identify the fire year and fire-prone months **at the pixel scale**, thereby extracting a broad and stable fire season for each grid cell (Fig. S2).

Comment 3: Fig. S2 – The first time we see use of the different ecoregions is Fig. S2 (first mentioned line 166), yet the abbreviations aren’t defined until Fig. 1 (line 213). I suggest either repeating the ecosystem names in the caption for Fig. S2 or introduce them earlier in the methods section

Response 3: We sincerely appreciate your careful review and constructive suggestions. As per your suggestions, we have introduced the ecoregion data using a separate paragraph and defined the full names and abbreviations of each ecoregion in the Methods section. This revision also ensures that the legend in Fig. 1 remains more concise and clearer.

[Page 8-9, Lines 152-157]

Our study area included 14 ecoregions north of 30°N, excluding tropical ecoregions (Fig. 1 a): polar (Polar), boreal mountain system (BRMS), boreal tundra woodland (BRTW), boreal coniferous forest (BRCF), temperate mountain system (TPMS), temperate desert (TPDT), temperate steppe (TPST), temperate continental forest (TPCF), temperate oceanic forest (TPOF), subtropical mountain system (STMS), subtropical desert (STDT), subtropical steppe (STST), subtropical dry forest (STDF), and subtropical humid forest (STHF).

[Page 13, Lines 233-234]

Fig. 2. Workflow for identifying threshold effects with an introduction to threshold regression models. (a) Ecoregions of mid–high northern latitudes.

Comment 4: L. 307 – You don't mention what happens between latitudes 30-35°N, 42-47°N, or higher than 60°N. For the two regions you talk about – are these results the strongest and weakest contributions of the different latitudes?

[Page 18, Line 307-308]

Threshold effects showed a stronger contribution (~30%) in the region between 47°N and 60°N, but a weaker contribution (~25%) in the region between 35°N and 42°N.

Response 4: We appreciate your valuable suggestion and have addressed your concern from two aspects:

- (1) We have rephrased this sentence to include the contribution of threshold effects in the remaining regions and hope that it is now clearer.
- (2) Yes, we have revised this sentence and confirmed that the regions between 47°N-60°N and 35°N-42°N show the strongest and weakest contributions, respectively.

[Page 19, Line 328-331]

The threshold effects contributed most significantly (~30%) in the region between 47°N and 60°N, while the weakest contribution (~25%) was observed between 35°N and 42°N. In comparison, the remaining regions showed a contribution of approximately 27%.

Comment 5: Fig. 6(a)-(f) – The units of km² seems small to me considering the values. Please check.

Response 5: Thank you. After careful checking, we confirm that the unit in Fig. 6(a)-(f) is km², and we have revised the figure captions to explicitly state this. All raster data in this study have been aggregated to a uniform spatial resolution of 0.25°. Thus, the future changes in burned areas (BA) during the fire season are aggregated within each 0.25° grid cell, with values ranging from -30 to 30 km².

[Page 23, Line 384-385]

(a)–(f) show the spatial distributions of changes in BA (unit: km² in a 0.25° grid cell) under the SSP1-2.6 and SSP5-8.5 scenarios in 2030–2050, 2051–2070, and 2071–2100.

Comment 6: L. 397 – “although...increase”. This seems an obvious point without further expansion. Consider removing.

[Page 18, Line 307-308]

Therefore, subtropical wildfires rapidly increase once these thresholds are exceeded⁵¹, although human control measures may mitigate this increase⁵².

Response 6: Thank you for your thoughtful comment. We agree that the role of human control measures may seem self-evident in this context. We have revised this sentence to provide more detail on the role of human activities in moderating subtropical wildfire changes. We also highlight the importance of sustained and effective interventions to curb the increasing trend of wildfires. We hope that our responses and the revised text meet with your approval.

[Page 26, Line 421-424]

Therefore, subtropical wildfires rapidly increase once these thresholds are exceeded⁵³. However, human control measures have exceeded their thresholds and moderated the changes in subtropical wildfires,

especially around densely populated areas, suggesting that sustained and effective interventions help curb the trend of increasing wildfires⁵⁴.

Comment 7: L. 418 – “Warming and drought...transport changes”. I agree this is an important clarification statement, but you don’t expand on the causes of high latitude fires elsewhere, so this sentence seems a little out of place.

[Page 26, Line 418-419]

Warming and drought intensified wildfires at high latitudes due to Arctic oscillations, sea-ice loss, and moisture transport changes^{20, 24, 60}.

Response 7: We appreciate your valuable comment and have carefully considered the issue you raised. As you pointed out, this sentence seemed somewhat out of place due to the lack of a clear logical flow.

- (1) We have revised the description of the region involved in the context to focus solely on high latitudes north of 50°N.
- (2) Additionally, we have incorporated logical connectors between the four sentences and made necessary revisions to clarify how threshold effects drive rapid changes in wildfires across high latitudes.
- (3) The revised paragraph further explains the causes of high-latitude wildfires in terms of threshold effects. We hope that these revisions address your concern and meet your approval.

[Page 27-28, Line 449-455]

Our results also highlight that threshold effects explained roughly one-third of wildfire variability, especially with the most significant impact at northern high latitudes (> 50°N) (Fig. 4; Fig. 5b). Currently, warming and drought intensified wildfires at high latitudes due to Arctic oscillations, sea-ice loss, and moisture transport changes^{20, 24, 60}. In this context, we argue that temperature, drought, and their threshold effects may interact to facilitate wildfires in high-latitude ecoregions (Fig. 5 c–d). For example, threshold effects amplified the promoting effects of warmer and drier conditions on wildfires, leading to an increase in large wildfires^{11, 61, 62}.

Comment 8: Throughout – the paper is excellently written; however, it occasionally may not always be understandable for people without a prior background knowledge of climate/fires/statistics. Before resubmission, consider asking a non-expert to read through the paper to point out potentially more confusing points which may need rewording.

Response 8: We appreciate your suggestion to make our paper more accessible to a broader audience from various disciplines. In response, we sought feedback from two non-expert colleagues and two academic language editors for this revised manuscript. Here, we summarize the identified issues in four aspects and have made some revisions accordingly. Additionally, other minor adjustments have been made throughout the manuscript. We hope these improvements align with your expectations. Below, we provide representative examples of our modifications:

- (1) The background should include a clear introduction to key concepts that will help improve logical

coherence between sentences.

Original: [Page 4, Line 66-67]

Similarly, cross-scale thresholds are recognized as key indications for revealing changes in fire size and multiscale interactions during the phase of wildfire spreading.

Revision: [Page 4, Line 66-68]

Similarly, cross-scale thresholds control fire size to transfer from smaller to larger scales (e.g., from landscape to regional scale), which are recognized as key properties for revealing changes in fire behaviors and multiscale interactions during the phase of wildfire spreading.

(2) When defining key concepts, it is recommended to prioritize clear, practical descriptions over mathematical language, aligning the explanation with the specific research context.

Original: [Page 11, Line 197-200]

Here, threshold (e) is defined as the point in x where y abruptly changes its value or its relationship with x . The threshold effect (TE) is defined as the overall change in slope after crossing the threshold, where positive values indicate enhancing effects and negative values signify weakening effects.

Revision: [Page 11-12, Line 214-218]

Here, threshold (e) is defined as the position on the x -axis, where the nonlinear relationship between wildfire (y -axis) and the driver (x -axis) shifts abruptly. The threshold effect (TE) is defined as the overall change in slope after the driver crosses this threshold. Positive value indicates that wildfire changes are enhanced after the driver exceeds the threshold (enhancing effect), while negative value suggests a weakening of wildfire changes (weakening effect).

(3) The description and interpretation of the results is somewhat unclear. It is recommended to use more intuitive quantitative metrics or specific examples to facilitate understanding.

Original: [Page 15, Line 266-268]

Conversely, regional averages for population exceeded their thresholds by 1.5 orders of magnitude, and current population variation somewhat weakened subtropical wildfire changes (Fig. 2 j).

Revision: [Page 15, Line 283-285]

Conversely, regional averages for population exceeded their thresholds by 1.5 orders of magnitude (~30 times), showing that current population variation largely weakened subtropical wildfire changes (Fig. 2 j).

(4) Long or complex sentences should be avoided and some confusing expressions should be broken down into several short sentences and explained individually.

Original: [Page 26, Line 407-410]

More importantly, correlations and covariation patterns among thresholds also suggest that changes in individual drivers may trigger ripple effects of wildfire responses, causing successive exceedances of interconnected thresholds⁵⁶ and obscuring the impact of threshold effects of individual drivers^{56, 57}.

Revision: [Page 27, Line 434-437]

More importantly, correlations and covariation patterns among thresholds also suggest that changes in individual drivers may trigger ripple effects of wildfire responses, causing successive exceedances of interconnected thresholds ⁵⁶.

Revision: [Page 27, Line 439-440]

Moreover, their threshold effects may interact with each other to obscure the spatial pattern of threshold effects of individual drivers ^{56, 57}.

Response to Reviewer #1 Comments

Reviewer #1 (Remarks to the Author):

The authors have done a superb job in providing clear and detailed responses to my previous comments. The work is novel and important for interpreting ongoing changes in burned area for higher latitudes (>30 degrees). The corresponding edits should make the manuscript clearer and more accurate. I have no further comments or issues with the manuscript and look forward to seeing it.

Response to reviewer #1:

We sincerely thank you for your dedicated efforts and thoughtful feedback during the review process. Your recognition of our work as "novel and important" is deeply encouraging and motivates us to pursue excellence in our research. We are also grateful for your acknowledgment of the clarity and accuracy of our revisions. Your support and insightful comments have greatly strengthened our manuscript, and we truly appreciate your time and expertise. With your continued support, we hope the paper will soon be published and contribute positively to wildfire research. Thank you once again for your invaluable contribution!

Response to Reviewer #2 Comments

Reviewer #2 (Remarks to the Author):

Thank you for taking the time to reply to my comments. I am satisfied with the responses and have no further significant suggestions, although would like to comment on your Response 5 and highlight a couple of typos or word changes for your consideration.

Response to reviewer #2 comments:

Thank you for your thoughtful feedback. We greatly appreciate your time and effort in reviewing our manuscript. Regarding your comments on Response 5, we have incorporated your suggestions and made the necessary revisions. Additionally, we have addressed the typos and wording changes you highlighted to ensure the manuscript is polished and error-free. Below, we provide detailed point-by-point responses to your comments. Each response includes: your comment (in red), the original text (in black), our response (in blue), and the revised text (in black) with corresponding pages and line numbers. Your insights have been invaluable, and we deeply appreciate your constructive input. Thank you once again for your support.

Comment to author Response 5:

Thank you for the clarification. I just wanted you to double check the numbers were accurate, so the additional clarification in Figure 6 probably isn't necessary as the units are given in the figure itself.

[Page 23, Line 383-385]

Compared with the annual mean BA of the historical period (2001–2022), (a)–(f) show the spatial distributions of changes in BA (unit: km² in a 0.25° grid cell) under the SSP1-2.6 and SSP5-8.5 scenarios in 2030–2050, 2051–2070, and 2071–2100.

Response to “Comment of Responses 5”: Thank you for your feedback. We have understood your intention and have double-checked the numbers. The additional clarification in the figure captions has been removed, as you suggested.

[Page 15, Line 232-234]

Compared with the annual mean BA of the historical period (2001–2022), (a)–(f) show the spatial distributions of changes in BA under the SSP1-2.6 and SSP5-8.5 scenarios in 2030–2050, 2051–2070, and 2071–2100.

Typos or word changes:

Comment 1: L. 67 – “landscape scale” sounds clunky. Consider “local” instead.

[Page 7, Line 66-68]

Similarly, cross-scale thresholds determine the transition in fire size from smaller to larger scales (e.g. from landscape scale to regional scale) and serve as key properties for revealing changes in fire behaviors and multiscale interactions during wildfire spread.

Response 1: Thank you for your suggestion. We have revised "landscape " to "local" in this sentence.

[Page 4, Line 65-67]

Similarly, cross-scale thresholds determine the transition in fire size from smaller to larger scales (e.g., from local scale to regional scale) and serve as key properties for revealing changes in fire behaviors and multiscale interactions during wildfire spread.

Comment 2: L. 68 – “fire behavior” tends to be singular rather than plural.

[Page 4, Line 66-68]

Similarly, cross-scale thresholds determine the transition in fire size from smaller to larger scales (e.g. from landscape scale to regional scale) and serve as key properties for revealing changes in fire behaviors and multiscale interactions during wildfire spread.

Response 2: Thank you for pointing this out. We have revised "fire behaviors" to "fire behavior" to ensure grammatical accuracy.

[Page 4, Line 65-67]

Similarly, cross-scale thresholds determine the transition in fire size from smaller to larger scales (e.g., from local scale to regional scale) and serve as key properties for revealing changes in fire behavior and multiscale interactions during wildfire spread.

Comment 3: L. 123 – Consider replacing “finally” with “ultimately”.

[Page 7, Line 122-124]

However, since multiyear average BA was finally used for analysis, the potential impact of this discrepancy on our results is relatively limited.

Response 3: We appreciate your kind suggestion and have replaced “finally” with “ultimately” in this sentence.

[Page 24, Line 377-378]

However, since multiyear average BA was ultimately used for analysis, the potential impact of this discrepancy on our results is relatively limited.

Comment 4: L. 451 – “Currently” doesn’t sound quite right. Consider “Warming and drought have intensified”.

[Page 7, Line 122-124]

Currently, warming and drought intensified wildfires at high latitudes due to Arctic oscillations, sea-ice loss, and moisture transport changes^{20, 24, 60}.

Response 4: We appreciate your thorough review and fully agree with you. The sentence has been revised to "Warming and drought have intensified" as recommended.

[Page 20, Line 300-302]

Warming and drought have intensified wildfires at high latitudes due to Arctic oscillations, sea-ice loss, and moisture transport changes^{20, 24, 36}.

Comment 5: Table S1 – The units of “Leaf Area Index” are either m^2/m^2 or $\text{m}^2 \text{ m}^{-2}$, not $\text{m}^{-2}/\text{m}^{-2}$. This occurs twice in the table.

[Supplementary Materials: Page 7, Line 122-124]

Table.S1. Summary of datasets and data availability statement.

Dataset Model	Variable Name	Unit	Time Series
MODIS MOD15A2H	Leaf Area Index	$\text{m}^{-2}/\text{m}^{-2}$	2001-2022 (8-day)
MPI-ESM1-2-HR	Leaf Area Index	$\text{m}^{-2}/\text{m}^{-2}$	2001-2100 (monthly)
FOA Global Ecological Zones	Global Ecological Zones	-	2010

Response 5: Thank you for pointing out the error in the units for "Leaf Area Index" in Table S1. We have corrected the units to " m^2m^{-2} " in both instances.

[Supplementary Table 5: Page 15, Line 100-102]

Supplementary Table 5. Summary of datasets and data availability statement.

Dataset Model	Variable Name	Unit	Time Series
MODIS MOD15A2H	Leaf Area Index	m^2m^{-2}	2001-2022 (8-day)
MPI-ESM1-2-HR	Leaf Area Index	m^2m^{-2}	2001-2100 (monthly)
FAO Global Ecological Zones	Global Ecological Zones	-	2010

Comment 6: Table S1 – “FOA Global Ecological Zones” should be “FAO ...”

Response 6: We thank the reviewer for pointing out this typographical error. We have corrected "FOA" to "FAO" in Supplementary Table 5 (see **Response 5**).

Comment 7: Appendix S2 doesn’t appear to be referenced in the main text.

Response 7: Thank you for pointing this out. “Appendix S2” has been renamed “Supplementary Note 1” in supplementary information. We have now cited “Supplementary Note 1” in the caption of Fig. 1 in the main text to ensure it is properly integrated and contextualized within the manuscript.

[Page 9, Line 143]

Supplementary Note 1 contains detailed information on the identification of threshold effects.

Comment 8: Table S4 – L. 111 – “Yellow the dashed line” should be rephrased.

[Supplementary Materials: Page 7, Line 122-124]

Yellow the dashed line, confidence interval, and label indicate that the threshold did not pass the Mann–Whitney U-test.

Response 8: We sincerely appreciate the reviewer's careful reading. This was a grammatical error, and we have removed "the" from this sentence.

[Supplementary Information: Page 5, Line 46-47]

Yellow dashed line, confidence interval, and label indicate that the threshold did not pass the Mann–Whitney U-test.

Comment 9: Figure S6 – L. 136 – Consider “comparison” instead of “comparing”

[Supplementary Materials: Page 7, Line 122-124]

To ensure the validity of introducing threshold parameters on model performance, we also fit another XGBoost model that used only the 11 original features without including their threshold parameters for **comparing** purposes.

Response 9: Thank you for this kind suggestion. We have revised the text to use "comparison" instead of "comparing" to improve clarity.

[Supplementary Fig.4: Page 10, Line 70-72]

To ensure the validity of introducing threshold parameters on model performance, we also fit another XGBoost model that used only the 11 original features without including their threshold parameters for **comparison** purposes.