nature portfolio

Peer Review File

Ladder fuels rather than canopy volumes consistently predict wildfire severity even in extreme topographic-weather conditions

Corresponding Author: Dr Christopher Hakkenberg

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

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

Version 0:

Decision Letter:

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

Dear Dr Hakkenberg,

Your manuscript titled "Ladder fuels, not canopy volumes, consistently associated with forest wildfire severity even in extreme topographic-weather conditions" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some 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.

Important: The response to reviewers must not include any figures, tables or graphs. If you wish to respond to the reviewer reports with additional data in one of these formats, please add them to the main article or Supplementary Information, and refer to them in the rebuttal. Due to current technical limitations, any figures, tables, or graphs embedded in your rebuttal will not be included in the peer review file, if published.

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

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
Link Redacted
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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,

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
@CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

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

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

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist: Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Dear Authors,

It was a pleasure to read your pioneering and valuable work. You have provided robust evidence that ladder fuels are a significant predictor of forest wildfire severity in California by utilizing 3D approaches, extensive data, and appropriate statistical methods. However, I have some comments and questions about your manuscript that I hope will help improve its quality, scientific soundness, and readability.

First, I recommend enhancing the article's structure and clarity by focusing on four issues:

1- Lines 84-85 describe your variables, which are crucial to understanding the entire work. However, the terms used may be challenging for a broad audience to visualize. This can be addressed by explaining the variables in plainer English and providing more understandable specifications in the methods section.

2- Throughout the document, there are several sentences that should be revised as they might lack clarity in their current form, such as “the increasing intensity in topographic…conditions” (L127) or “up until larger values of fuel structure” (L174).

3- Probably the most important issue, I feel that the manuscript's structure needs improvement. For instance, the authors return to introductory text (L130-142) after setting the objectives and hypotheses (L119-129). The discussion needs to be more concise, easily followed, and focused on the results presented, with less introductory text.

4- I recommend revising and improving the alignment between the statements and the references throughout the document. For instance, Ref. 4 is not very appropriate in L38, as it explores fire probability rather than fire size and severity. Regional and global studies focusing on trends and patterns of fire size and severity would be more appropriate than Ref. 4. Refs 20 and 26 in L79 were used to highlight the potential of GEDI, but these studies do not use GEDI data. Ref 32 is probably not the best to justify the use of dNBR (although referred to offsets), as this reference proposes a different spectral index of burn severity.

Second, I have some questions about the response and predictor variables:

- dNBR is a spectral index based on the reflectance of SWIR and NIR bands, which is also affected by species composition and land cover in general. Thus, different dNBR values might be achieved in different vegetation types for the same degree of biomass consumption and overall impact. How do you think this might affect your results?

- If I understood correctly, the variable “Ladder fuels” (L460) is considered only in sites with a canopy height higher than 10m. Thus, your sample for ladder fuels is not the same as for the rest. How do you think this might affect your results? In addition, other well-established LiDAR variables that inform forest vertical structure had been omited. This should be partially justified in the methods section.

Line-by-line comments:

L17: Not all wildfires occur in forests.
L22: Please revise the writing. Is “that” missing before GEDI?
L43: Which function?
L93: Defines burn severity, including ecological responses. This is quite contentious, and according to Keeley (2009) in a well-accepted paper by the scientific community, both concepts should be separated.
L96: There are burn severity metrics that are not so ocular (e.g., DBH mortality).
L103: Please replace “per-fire” with “pre-fire.”
L113: VPD and ET abbreviations should be described earlier.
L175: Don’t they covary with mPAI too?
L261: I recommend breaking the sentence after "platform." However, reconsider the extent of L260-264 as it is partially repetitive with the introduction.
L271: The studied pre-fire fuel structure metrics.
L275: Please provide a reference.
L318-319: Your results do not confirm the ability of GEDI to estimate ladder fuels. This should be confirmed in different ways (e.g. with accuracy metrics or some other kind of demonstration)
L355: This statement is erroneous,please revise. The pre-print reference you have provided, as well as many references globally, indicate that higher productivity is associated with higher potential for short fire return intervals.

I hope these suggestions and comments are helpful and contribute to see the article published in COMMSENV

Reviewer #2 (Remarks to the Author):

The authors employ GEDI-based spaceborne LiDAR to characterize pre-fire fuel structures across California and quantify the interplay of fuel, topography, and weather in driving the severity of 42 wildfires between 2019 and 2021. This topic is significant to the wildfire and forestry community. The main finding of this study is the empirical evidence that ladder fuels, rather than canopy volumes, are consistently associated with forest wildfire severity even under extreme topographic-weather conditions. The research design is clear, with well-organized writing. Below are a few comments and suggestions for further enhancement.

The authors extract biomass, canopy height, layering, and ladder fuels using the GEDI waveforms. What is the data quality situation across California? Additionally, how do variations in data quality, especially in dense canopy areas or regions with complex topography, affect the reliability of the results?

The drivers of wildfire progression between northern and southern California are contrasting; the authors should address this point with additional analysis.

The conclusion wraps up the discussion nicely. One additional point regarding the implications: How do the findings of this study translate into actionable strategies for forest management, particularly in regions similar to California but with less advanced monitoring capabilities?

This study focuses on large wildfires (>2000 ha). What are the situations for medium and small-sized wildfire burn severity? It is suggested that the authors include some discussion on this point.

Reviewer #3 (Remarks to the Author):

The manuscript presents an application of GEDI products to characterize fuel structure and its relationship to severity and topographic climatic conditions. The work seems promising, however the absence of methodology makes it impossible to evaluate the results presented. I encourage authors to submit a complete manuscript with methodological information so that it can be evaluated.

Version 1:

Decision Letter:

Dear Dr Hakkenberg,

Your manuscript titled "Ladder fuels, not canopy volumes, consistently predict wildfire severity even in extreme topographic-weather conditions" 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.

EDITORIAL REQUESTS:

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

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

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

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

SUBMISSION INFORMATION:

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

OPEN ACCESS:

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

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

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

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

Best regards,

Mengjie Wang
Associate Editor
Communications Earth & Environment
@CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Dear authors,
Thank you very much for your response to my previous comments and the edits made on the document.
My assessment is that you have done an excellent work in addressing all the comments, and that the manuscript is acceptable for publication in the current form.

Reviewer #2 (Remarks to the Author):

Thanks for addressing my comments and questions. I recommend it for acceptance

benefits**

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Dear Authors,

It was a pleasure to read your pioneering and valuable work. You have provided robust evidence that ladder fuels are a significant predictor of forest wildfire severity in California by utilizing 3D approaches, extensive data, and appropriate statistical methods. However, I have some comments and questions about your manuscript that I hope will help improve its quality, scientific soundness, and readability.

First, I recommend enhancing the article's structure and clarity by focusing on four issues:

- Lines 84-85 describe your variables, which are crucial to understanding the entire work. However, the terms used may be challenging for a broad audience to visualize. This can be addressed by explaining the variables in plainer English and providing more understandable specifications in the methods section.
    - Thank you for this comment, which helped us break out of our forest structure and GEDI metrics bubbles. As part of a general revision of the Introduction (in response to R1's comments below) we moved Fig. 2 to the Introduction to help better visualize these height metrics with respect to their vertical distributions and improved the figure's axis labels and caption for clearer description.

    - In addition, we added the following explanatory text to the Introduction:
        - *Layering can be envisioned as the total number of distinct canopy layers, such that more layers generally correspond to greater canopy heights as well as greater continuity of fuels from the ground to the top of the canopy (Fig. 2). Ladder fuels, on the other hand, are defined as fuels between 0-10m that can propagate flames from the ground stratum (0-5m) to tree crowns (>10m). Because of this specific requirement for at least three 5m PAI bins (a result of physical constraints from GEDI's pulse width[1]) from which to define GEDI-based ladder fuels, it is only applicable to forests with canopy heights over 10m (See Methods: GEDI fuel structure).*

    - Furthermore, the Methods section has been bolstered with additional text explaining the two novel metrics to a more general audience:
        - *Biomass and height are common indicators of fuel volumes[2,3], while layering and ladder fuels are GEDI-determined indicators of vertical continuity in fuel structure (despite significant correlation; Fig. S4.3). Importantly, ladder fuel metrics are only applicable for forests >10m due to the physical constraints of GEDI's pulse width, which is optimized for detection of PAI in 5m vertical bins[1].*

    - Finally, we added some explanatory text to the legend of Fig. 3 to enhance clarity on the relationship between the GEDI-derived metrics and the structural attributes they represent.

- Throughout the document, there are several sentences that should be revised as they might lack clarity in their current form, such as "the increasing intensity in topographic…conditions" (L127) or "up until larger values of fuel structure" (L174).
    - Thank you for pointing this out. We have heavily revised the Introduction to improve clarity and readability. There are many examples in the revised (track changes) document that attest to the changes. More instances are described below, but to your two specific example, they were revised as follows:
        - *...increasing topographic slope and more intense fire weather conditions...*
        - *...until they peak at larger relative values of fuel structure (z-score >1).*

- Probably the most important issue, I feel that the manuscript's structure needs improvement. For instance, the authors return to introductory text (L130-142) after setting the objectives and hypotheses (L119-129).
    - We have taken this comment to heart and rethought the ordering of the Introduction's components. So, for example, you will see the offending final paragraph moved upwards to follow the paragraph that introduces how fuel~structure relationships vary across topo-weather gradients and their implications – thereby setting up the main question motivating the paper. This change likewise meant moving Fig. 1 from the Results. Following this, we introduce the key metrics used to address the question just posed: structural and severity metrics (with increased discussion of the four metrics for better comprehension -which was a comment noted by R1 above) and moved the corresponding Fig. 2 up from Results. Next, we moved the data Table 1 from the Methods to this brief discussion on data. Finally, the Introduction now concludes with the hypotheses (as recommended).

- The discussion needs to be more concise, easily followed, and focused on the results presented, with less introductory text.
    - The introductory text has been removed so that the Discussion now immediately jumps into contextualizing results.

    - We have also generally heavily edited the text to focus closely on our results, contextualized by findings from other studies.

- I recommend revising and improving the alignment between the statements and the references throughout the document. For instance, Ref. 4 is not very appropriate in L38, as it explores fire probability rather than fire size and severity. Regional and global studies focusing on trends and patterns of fire size and severity would be more appropriate than Ref. 4.
    - Thank you for pointing this out. We agree with your assessment and have removed Ref 4 (Chen etal 2021).

    - While we feel the other two citations provide sufficient reference, owing to the importance of the topic, we added a third[4].

- Refs 20 and 26 in L79 were used to highlight the potential of GEDI, but these studies do not use GEDI data.
    - Refs 20 and 26 were originally intended to highlight "readily-applicable analogues to traditional wildfire fuel structure parameters" and thus it was not deemed necessary that they be GEDI derived. That said, we take the reviewers point, and have replaced the references with studies from two spaceborne lidar sensors[5,6].

- Ref 32 is probably not the best to justify the use of dNBR (although referred to offsets), as this reference proposes a different spectral index of burn severity.
    - We have changed the reference. There are many studies that come to a similar conclusion, but we found Miller et al. 2023 most appropriate as it both demonstrates the increased usage of dNBR through meta-analysis of sorts, and it contains a section on offsets[7].

Second, I have some questions about the response and predictor variables:

- dNBR is a spectral index based on the reflectance of SWIR and NIR bands, which is also affected by species composition and land cover in general. Thus, different dNBR values might be achieved in different vegetation types for the same degree of biomass consumption and overall impact. How do you think this might affect your results?
    - This is a great question. We address it (and related questions regarding variability across a large study domain) in a few ways:
        - First, a primary strength of GEDI, and our large sample approach, is that it averages variability across >830K samples. While there is a lot of natural variation in the relationship between biomass consumption and dNBR values, noise generated from the aggregated categories is mitigated by having such a large sample size, from which dominant patterns can be determined.

        - Second, by employing offset dNBR – which is based in part on forest type, especially its phenology – we partly account for varying severity~ dNBR relationships between regions.

        - Third, we include a supplementary figure that partitions the full dataset into components of conifer, broadleaf, and mixed forest types as well as by region (which is related to composition). These supplementary analyses show consistency between the full dataset and individual subsets, and help contextualize and corroborate final results.

        - Fourth, as this is acknowledged to be an open question, several sentences in the Discussion address pitfalls and caveats of optical-based severity indicators.

        - Finally, because this is such an important and complicated question (beyond the scope of this study), we note that we are actively investigating this question of dNBR~biomass removal, with the hypothesis that GEDI estimates might inform better severity measurements, or at least indicate if/which places/conditions dNBR breaks down. The manuscript will soon be *In Review*.

- If I understood correctly, the variable "Ladder fuels" (L460) is considered only in sites with a canopy height higher than 10m. Thus, your sample for ladder fuels is not the same as for the rest. How do you think this might affect your results?
    - This is a great point, and one that we pondered and discussed prior to and during analyses. An alternative metric could assess all samples that possess canopy heights >=5m. Essentially, this would lower the criteria for $mPAI_{10m}$ so that it is consistent with the other metrics that are all >=5m. However, we believe, doing so would conflate low-stature forest with actual ladder fuels, whereby ladder fuels are understood in the specific context of GEDI, and GEDI PAI's pulse-width determined 5m vertical resolution. Owing to GEDI's physical constraints, there must be at least three 5m strata (0-5m, 5-10m, and >10m) to qualify as a GEDI-determined ladder fuel, which as the name implies serves as a ladder for flames from one stratum below to one stratum above. Thus, to ensure that we were assessing the appropriate measure at the appropriate GEDI-determined vertical resolution and its associated limits of vertical range, we had to define ladder fuels as >10m.

    - Alternatively, we could change all other metrics to >10m, but this would limit our ability to assess GEDI-derived metrics for canopy heights between 5-10m, like biomass and height. Thus we added a supplement exploring this option (see below), but opted to keep the original metric definitions in the main text.

    - This, of course, explains our rationale rather than addressing your question specifically. To answer your question, and anticipate the same from readers, we have added a new Supplement (S5) whereby we change all other metrics to >10m and thus limit the sample size to be equal for all metrics. As you can see from S5, Figures S5.1-3, this process reduced the sample size from 830,709 to 734,592 samples, or an 11.6% reduction. Despite that cut, the supplementary results indicates no substantial effect on our conclusions. While Fig. S5.2 does show an increase in nonsignificant partial effects between biomass and severity compared with a dataset without the >10m constraint, that finding actually reinforces the result in Fig. 5 (and Fig. S5.3) that biomass is indeed very dependent on topo-weather for its effect on severity. While corroborating the result of Fig. 5, we interpret this loss of significance (and corresponding increase in CIs) as resulting primarily from the elimination of shorter stature forests, whereby the removal of the lower end of the values results in models with less total variance. Furthermore, and as noted above, this removal of forests with heights between 5-

10m would limit our interpretation of biomass-severity relationships for a host of dominant forest types in the study domain, such as short-statured oaks.

- In addition to the new supplement S5, we added the following text to the Introduction:
  - *Ladder fuels, on the other hand, are defined as fuels between 0-10m that can propagate flames from the ground stratum (0-5m) to tree crowns (>10m). Because of this specific requirement for at least three 5m PAI bins (a result of physical constraints from GEDI's pulse width[1]) from which to define GEDI-based ladder fuels, it is only applicable to forests with canopy heights over 10m (See Methods: GEDI fuel structure).*
- Discussion:
  - *While the sample size for ladder fuels was smaller than that of the other three metrics (734,347 GEDI footprints for ladder fuels versus 830,709 for biomass, height and layering; or an 11.6% reduction), this sample size differential had no substantial effect on findings (See S5).*
- and Methods:
  - *Importantly, ladder fuel metrics are only applicable for forests >10m due to the physical constraints of GEDI's pulse width, which is optimized for detection of PAI in 5m vertical bins[1]. This 5m binning size likewise balances the need for a sufficient signal from which to accurately characterize PAI (an aggregate value of plant area in a pre-defined volume) while still providing the best possible vertical resolution. Because of this GEDI-determined constraint, "ladder fuels" are defined as the amount of canopy fuels between 0-10m that can serve to propagate flames from one 5m layer below (the 0-5m ground stratum) to one layer above (tree crowns >10m)[8]. Therefore, the sample size for ladder fuels was smaller than that of the other three metrics (734,347 GEDI footprints for ladder fuels versus 830,709 for biomass, height and layering; or an 11.6% reduction in sample size; See S5).*

- In addition, other well-established LiDAR variables that inform forest vertical structure had been omited. This should be partially justified in the methods section.

  - First, we added the following text to the Methods:
    - *While most GEDI-derived fuel structure metrics possess varying degrees of correlation (See Fig. S4.3), the aforementioned four metrics were chosen based on the following criteria: (a) they should be easily interpretable to remote sensing and fire science research and management communities, (b) they should be well-distributed across a range of canopy height, volume and heterogeneity categories[2], (c) they should each show promise to independently predict wildfire severity across the study domain, and (d) they should balance precedence in the literature with novelty for new predictors. Thus, while total biomass and canopy height are well-established in the literature[2,3,5], GEDI-derived layering and ladder fuels*

are novel metrics proposed to better characterize under-represented aspects of vertical fuel continuity, especially in the subcanopy[9].

- Second, we added a dataset to our Zenodo link to clarifies the other laternative metrics we looked at:
  - *From many potential GEDI-derived canopy metrics*[10]*...*

- Line-by-line comments:

  - L17: Not all wildfires occur in forests.
    - Corrected from "...wildfire severity include forest fuels..." to "...forest wildfire severity include fuels..."

  - L22: Please revise the writing. Is “that” missing before GEDI?
    - “that” has been added

  - L43: Which function?
    - This is a good point of clarification. We have revised the text away from general “function” and towards specific landscape properties and processes: “biodiversity, habitat, and resilience” and added three references that each highlight one of these “functions”[11–13].

  - L93: Defines burn severity, including ecological responses. This is quite contentious, and according to Keeley (2009) in a well-accepted paper by the scientific community, both concepts should be separated.
    - This is a great point. The text was revised as follows:
      - *Wildfire effects were characterized in terms of severity, which we define as the proportion of aboveground organic matter directly consumed (combusted) by fire*[14]*. This is in contrast to longer-term, lagged ecosystem responses like delayed tree mortality and vegetation resprouting*[15].

  - L96: There are burn severity metrics that are not so ocular (e.g., DBH mortality).
    - We appreciate this point but the phrase “ocular” here is specifically in reference to CBI, which is a field-based ocular estimate. We have clarified this as follows:
      - *...the Composite Burn Index (CBI) excel for accurately characterizing site-level severity. However, because the CBI relies primarily on ocular estimates ...*

  - L103: Please replace “per-fire” with “pre-fire.”
    - “per-fire” is the correct term to describe how each dNBR offset is specific to a fire. We added a short clarifier on this to the caption of Fig. 6.

  - L113: VPD and ET abbreviations should be described earlier.
    - Correction made

- L175: Don't they covary with mPAI too?
    - Yes, they certainly do. All GEDI-derived fuel metrics possess varying degrees of correlation (see Supp. Figure S4.1). This is to be expected, as metrics were selected for interpretability and representativeness, rather than statistical independence like you'd want if they were together input into a multivariate regression. This sentence is in reference to H1, which specifically refers to the positive relationship between fuel and severity.

- L261: I recommend breaking the sentence after "platform." However, reconsider the extent of L260-264 as it is partially repetitive with the introduction.
    - This sentence was removed in response to the comment above to reduce introductory material from the Discussion.

- L271: The studied pre-fire fuel structure metrics.
    - Correction made

- L275: Please provide a reference.
    - We used the Meddens reference, which had previously been below, as a more general citation. And then a more specific one (Krawchuk et al. 2016) for the sentence referencing topographic controls[16].

- L318-319: Your results do not confirm the ability of GEDI to estimate ladder fuels. This should be confirmed in different ways (e.g. with accuracy metrics or some other kind of demonstration)
    - This is a great point, and highlights an interesting potential study which could use field-estimated ladder fuels to verify the lower stratum GEDI signal. We have changed the wording to more accurately reflect just what our data confirm:
        - *These results confirm the ability of GEDI waveforms to consistently estimate lower canopy fuel structure despite challenges with lidar signal attenuation in the lowest reaches of dense, high biomass forests*

- L355: This statement is erroneous, please revise. The pre-print reference you have provided, as well as many references globally, indicate that higher productivity is associated with higher potential for short fire return intervals.
    - Thank you for catching this. The characterization of fire return interval as long instead of short was a typo. We have revised as follows:
        - *This observation is consistent with a recent study that found that given extreme fire weather conditions, excess fuel volumes and ignition, more productive regions may burn at the highest levels of intensity*[17].

Reviewer #2 (Remarks to the Author):

- The authors employ GEDI-based spaceborne LiDAR to characterize pre-fire fuel structures across California and quantify the interplay of fuel, topography, and weather in driving the severity of 42 wildfires between 2019 and 2021. This topic is significant to the wildfire and forestry community. The main finding of this study is the empirical evidence that ladder fuels, rather than canopy volumes, are consistently associated with forest wildfire severity even under extreme topographic-weather conditions. The research design is clear, with well-organized writing. Below are a few comments and suggestions for further enhancement.
    - Many thanks for the compliment and encouragement.

- The authors extract biomass, canopy height, layering, and ladder fuels using the GEDI waveforms. What is the data quality situation across California? Additionally, how do variations in data quality, especially in dense canopy areas or regions with complex topography, affect the reliability of the results?
    - GEDI data is subject to intensive validation across a network of international sites[18], as well as from many independent studies (including one from the authors)[19–22]. These data are high quality inasmuch as they have been subjected to rigorous error characterization and uncertainty analysis. While these results hold globally, none of these validations explicitly addresses California, though we expect consistency. That said, a manuscript *In Review* from some European colleagues does in fact find GEDI data to be "high quality" (with errors assessed versus concurrent airborne lidar) for Trinity Mtns, CA.
    - As for the second question, these are each known issues with GEDI, though researchers (including us in this study) seem to be converging on a consistent approach:
        - For dense canopy, we enacted rigorous beam sensitivity thresholds, but failed to note this in the text. We thank the reviewer for reminding us of this omission and have added the following two points on filtering to the Methods: GEDI fuel structure:
            - *(6) possessing surface flag equal to 1 and the stale return flag equal to 0; and (7) having beam sensitivity >0.9 for the default ground finding algorithm and sensitivity of >0.95 for ground finding algorithm 2*[22]
        - For slopes, we enacted a slope threshold filter of 25 degrees based on preliminary tests and related studies (see rows 442-443 of original submission).

- The drivers of wildfire progression between northern and southern California are contrasting; the authors should address this point with additional analysis.
    - The reviewer brings up a great point (one that is echoed in their next two points as well) about generalization of our results to other study areas. While we are precluded from making explicit statements about regions outside of our data and study domain, we address the reviewer's point in two ways:

        - (1) While our study domain did not include Southern California, it did include the Central Coast (CC) which in some ways shares climatic and

compositional characteristics with Southern California. As such, using climate as a stand-in for latitude (as latitude is often a proxy for the underlying climatic drivers of severity patterns) could be a promising future approach. For example, in Fig. 6. we see that with increasing aridity and temperature seasonality (which could be expected for some of Southern California), the strength of the relationship between biomass and severity (e.g. the beta slope coefficient value) increases. Similarly, in Supplement S3, Figure S3.1a, we can further glean information on the unique status of the Central Coast forests, which as mentioned above, likely share some characteristics with Southern California. Unfortunately, a problem with this regional based subset is that it actually conflates very different forest types – for example, the Redwoods of the CZU Complex, and the open oak shrublands in the Mineral fire. This is why we ultimately decided the regional approach was not sufficient for the main text, but instead for a Supplement.

- (2) Owing to these points above, we added the following text:
  - *While it is ill-advised to directly extrapolate results from this study to regions outside of the study domain, future research could address the utility of using climate proxies to assess how relationships between fuels, topo-weather and severity generalize to other regions. For example, does this study's finding that biomass and severity were more tightly coupled in increasingly arid regions hold in other Mediterranean regions? How do differential drivers of fire progression – including wind speed and direction as well as landscape treatment design – affect relationships outside of the study domain?*

- In the future, we would like to expand the GEDI-based approach for complementary analyses in other regions.

- The conclusion wraps up the discussion nicely. One additional point regarding the implications: How do the findings of this study translate into actionable strategies for forest management, particularly in regions similar to California but with less advanced monitoring capabilities?
  - As with the point above, we are inspired to further consider application outside of the study domain. Indeed, the monitoring capabilities of GEDI are in no way diminished outside of California, provided the target region is below 52 degrees latitude, as that is GEDI's northernmost range. All other data is available for the rest of the contiguous USA. Thus, this analysis should be replicable anywhere outside of California, provided it stays within GEDI's near-global extent (i.e. no boreal forests). As such, we have added the following text:
    - *Inasmuch as high-quality data on weather conditions is available, GEDI fuel structure metrics provide a novel and complementary tool to guide forest management, including pre-fire treatment and suppression, especially for regions lacking ALS monitoring capabilities. Even though*

the ISS's orbital constraints result in increasing coverage with increasing latitude (until the orbital extents of 52 degrees latitude north and south), GEDI's near-global consistency makes its application for pre-fire fuels characterization promising across disparate regions and near-global ecosystem types[20,21].

- This study focuses on large wildfires (>2000 ha). What are the situations for medium and small-sized wildfire burn severity? It is suggested that the authors include some discussion on this point.
    - This is a great question. Owing to GEDI's sampling coverage, we could not assess smaller fires, lest we reduce our sample size so much that it would run afoul of assumptions underlying the spatial-GLMM models. While time will reduce this limitation as GEDI coverage increases, we have addressed this current limitation specifically in the same Discussion section as follows:
        - *Despite the promise of broad-scale application, GEDI samples – especially in lower latitude regions – may be too sparsely distributed to effectively assess small-medium sized fires (<2000ha) or where spatio-temporal resolution is critical to management intervention such as when assessing small-scale prescribed burns.*

Reviewer #3 (Remarks to the Author):

- The manuscript presents an application of GEDI products to characterize fuel structure and its relationship to severity and topographic climatic conditions. The work seems promising, however the absence of methodology makes it impossible to evaluate the results presented. I encourage authors to submit a complete manuscript with methodological information so that it can be evaluated.
    - The reviewer seems to not be aware of the Methods section being included. It is available in the original submission as well as in this revised submission (post review).

References

1. Dubayah, R. *et al.* GEDI L2B Canopy Cover and Vertical Profile Metrics Data Global Footprint Level V002, distributed by NASA EOSDIS Land Processes DAAC, https://doi.org/10.5067/GEDI/GEDI02_B.002. Accessed 2023-07-20. (2021).
2. Atkins, J. *et al.* Integrating forest structural diversity measurement into ecological research. *Ecosphere* **14**, e4633 (2023).
3. Hakkenberg, C. R. & Goetz, S. J. Climate mediates the relationship between plant biodiversity and forest structure across the United States. *Global Ecology and Biogeography* **30**, 2245–2258 (2021).
4. Iglesias, V., Balch, J. K. & Travis, W. R. U.S. fires became larger, more frequent, and more widespread in the 2000s. *Sci. Adv.* **8**, eabc0020 (2022).
5. Aragoneses, E., García, M., Ruiz-Benito, P. & Chuvieco, E. Mapping forest canopy fuel parameters at European scale using spaceborne LiDAR and satellite data. *Remote Sensing of Environment* **303**, 114005 (2024).

6. Garcia, M. *et al.* Characterization of canopy fuels using ICESat/GLAS data. *Remote Sensing of Environment* **123**, 81–89 (2012).
7. Miller, C. W., Harvey, B. J., Kane, V. R., Moskal, L. M. & Alvarado, E. Different approaches make comparing studies of burn severity challenging: a review of methods used to link remotely sensed data with the Composite Burn Index. *Int. J. Wildland Fire* **32**, 449–475 (2023).
8. Forbes, B. *et al.* Comparing Remote Sensing and Field-Based Approaches to Estimate Ladder Fuels and Predict Wildfire Burn Severity. *Front. For. Glob. Change* **5**, 818713 (2022).
9. Kramer, H. *et al.* Estimating Ladder Fuels: A New Approach Combining Field Photography with LiDAR. *Remote Sensing* **8**, 766 (2016).
10. Hakkenberg, C. R. Code and data for: Ladder fuels, not canopy volumes, consistently associated with forest wildfire severity even in extreme topographic-weather conditions. (2024).
11. Lesmeister, D. B. *et al.* Mixed-severity wildfire and habitat of an old-forest obligate. *Ecosphere* **10**, e02696 (2019).
12. Parks, S. A., Holsinger, L. M., Miller, C. & Nelson, C. R. Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression. *Ecological Applications* **25**, 1478–1492 (2015).
13. Perry, D. A. *et al.* The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. *Forest Ecology and Management* **262**, 703–717 (2011).
14. Keeley, J. E. Fire intensity, fire severity and burn severity: a brief review and suggested usage. *Int. J. Wildland Fire* **18**, 116–126 (2009).
15. Cansler, C. A. & McKenzie, D. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. *Ecological Applications* **24**, 1037–1056 (2014).
16. Krawchuk, M. A. *et al.* Topographic and fire weather controls of fire refugia in forested ecosystems of northwestern North America. *Ecosphere* **7**, e01632 (2016).
17. Coppoletta, M. *et al.* Fire history in northern Sierra Nevada mixed conifer forests across a distinct gradient in productivity. Preprint at https://doi.org/10.21203/rs.3.rs-4278120/v1 (2024).
18. Duncanson, L. *et al.* Aboveground biomass density models for NASA's Global Ecosystem Dynamics Investigation (GEDI) lidar mission. *Remote Sensing of Environment* **270**, 112845 (2022).
19. Tang, H. *et al.* Evaluating and mitigating the impact of systematic geolocation error on canopy height measurement performance of GEDI. *Remote Sensing of Environment* **291**, 113571 (2023).
20. Dorado-Roda, I. *et al.* Assessing the Accuracy of GEDI Data for Canopy Height and Aboveground Biomass Estimates in Mediterranean Forests. *Remote Sensing* **13**, 2279 (2021).
21. Li, X. *et al.* Validating GEDI tree canopy cover product across forest types using co-registered aerial LiDAR data. *ISPRS Journal of Photogrammetry and Remote Sensing* **207**, 326–337 (2024).
22. Burns, P., Hakkenberg, C. R. & Goetz, S. J. Multi-resolution gridded maps of vegetation structure from GEDI. *Sci Data* **11**, 881 (2024).