Responses to Reviewer #2: RC2

We sincerely appreciate your thorough evaluation and thoughtful feedback on our manuscript. Below, you can find the answers and explanation to all points you raised. All comments were incorporated in the revised manuscript.

On behalf of all co-authors,

Anna Trigubenko

General comments:

Reviewer#2: Statistical analysis are missing to support their findings

Response: We appreciate the reviewer's comment regarding the need for stronger statistical support. In the revised manuscript, we will include additional analyses to address this concern. Specifically, we will provide detailed geographical, structural and dendrochronological characteristics of the sampled sites, categorized by tree health status. We will also incorporate Basal Area Increment (BAI) calculations to better illustrate growth differences among healthy, damaged, and dead trees. Furthermore, we will present growth-climate and $\Delta^{13}C$-climate analyses, even in cases where correlations appear weak, in order to illustrate the potential influence of climate on tree physiology.

Reviewer#2: Methodology is lacking details:

- Both site descriptions are missing: for example, tree height, species, age, beetle infestation…

Response: Thank you for your comment. We agree this information was not sufficiently detailed or clearly structured in the original manuscript. In the revised version, we will expand the description of the study site. Additionally, we will include descriptive tables summarizing key stand and dendrochronological characteristics for each site to improve readability.

- No clear characterization for healthy, damaged and dead trees. I assume the identification was done visually. What are the exact criteria

Response: We thank the reviewer for the important comment. We apologize for the lack of clarity regarding the tree health classification criteria. The classification for the Zao site was based on the categories proposed by Leidemer et al. (2025), who defined six distinct tree health classes. These were: healthy (no visible defoliation), light Damage (up to 20% defoliation), medium damage (21-50% defoliation), heavy damage (over 50% defoliation), dead (100% defoliation), and fallen (tree

lying on the ground). The level of defoliation is based on the proportion of white pixels to the total number of pixels within a tree canopy in images taken by Unmanned Aerial Vehicles (UAVs) In order to enhance the performance of the YOLO (deep learning model) classification model, two additional dummy categories were included: artificial object and human. The initial categorization was indeed performed visually, using high-resolution aerial imagery and field validation as supporting references.

- How many cores were used for tree ring data

Response: Two cores were extracted per tree. One of the two cores was used for tree-ring width analysis and the other one for stable carbon analysis. In total, 20 trees for each health category were used for tree-ring width analysis.

Reviewer#2: No clear link between climate factors and beetle infestation is visible, as no statistical analysis were included

Response: We acknowledge the importance of exploring climatic influences on beetle-related tree decline. To address this, we will conduct a correlation analysis between monthly mean air temperatures during the growing season (April to September) and tree-ring widths for each health category. The analysis covered the period from 1993 to 2022 for healthy and damaged trees, and from 1993 to 2016 for dead trees (due to the tree death dates). The results revealed very weak correlations across all categories. For example, healthy trees showed the highest R^2 in April (0.08), while damaged and dead trees exhibited even lower values. The only relatively notable correlation was observed in May for dead trees ($R^2 = 0.16$), though still not statistically significant.

Given the consistently poor correlation results, we decided not to include these data in the manuscript. However, we recognize their relevance in supporting the conclusion that temperature alone is not a sufficient explanatory factor for beetle infestation dynamics.

Line comments:

L20-22. Please check sentence structure

Response: We will modify the sentences for better clarity as follows:

At the treeline of the Zao Mountains in northeastern Japan, a dual pest outbreak involving the tortrix moth (*Epinotia piceae*) and bark beetles (*Polygraphus proximus*) has caused severe mortality events in natural *Abies mariesii* forests. This is the first reported case worldwide of treeline retreat caused by bark beetle infestation.

L36. Replace with «these events»

Response: Done.

L60-69. Please add references

Response: Thank you for your comment. We will add appropriate references to support the paragraph. The revised text will read as follow:

As with other bark beetles, once *Polygraphus proximus* populations reach outbreak levels, they are capable of infesting even healthy trees. Such outbreaks, similar to those caused by the mountain pine beetle (*Dendroctonus ponderosae*), have led to the mortality of seemingly healthy trees across millions of hectares (Raffa et al., 2008). In the Zao Mountains, a large-scale bark beetle outbreak between 2012 and 2016 resulted in the devastation of pristine *Abies mariesii* forests over hundreds of hectares, especially those close to the treeline. This outbreak has drastically altered the landscape and is expected to have long-term ecological consequences in the region (Takagi, 2022). Bark beetle infestations not only reduce timber production and quality but also disrupt nutrient cycling, carbon uptake, and ecosystem biodiversity (Jönsson et al., 2009), highlighting the far-reaching impacts of these disturbances. Bark beetle-induced tree mortality also reduces the recreational and economic value of forests, affecting human health, tourism, and local livelihoods (Seidl et al., 2011).

References:

Raffa, K.F., Aukema, B.H., Bentz, B.J., et al.: Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. BioScience, 58(6), 501-517, https://doi.org/10.1641/B580607, 2008.

Takagi, E.: Host preference of the tree-killing bark beetle *Polygraphus proximus* across a geographic boundary separating host species, Entomologia Experimentalis et Applicata 170(11), https://doi.org/10.1111/eea.13229, 2022.

Jönsson, A.M., Appelberg, G., Harding, S., & Bärring, L.: Spatio-temporal impact of climate change on the activity and voltinism of the spruce bark beetle, *Ips typographus*. Global Change Biology, 15(2), 486-499, https://doi.org/10.1111/j.1365-2486.2008.01742.x, 2009.

Seidl, R., Schelhaas, M.J., & Lexer, M.J.: Unraveling the drivers of intensifying forest disturbance regimes in Europe. Global Change Biology, 20(9), 2785-2799, https://doi.org/10.1111/j.1365-2486.2011.02452.x, 2011.

L71. Which area is meant with «affected area». Zao mountains?

Response: Thank you for your comment. By “affected area” we refer specifically to the portion of the Zao Mountains that has been impacted by bark beetle infestation. We will clarify this terminology in the revised manuscript to avoid any ambiguity.

L81-83. Please check sentence structure

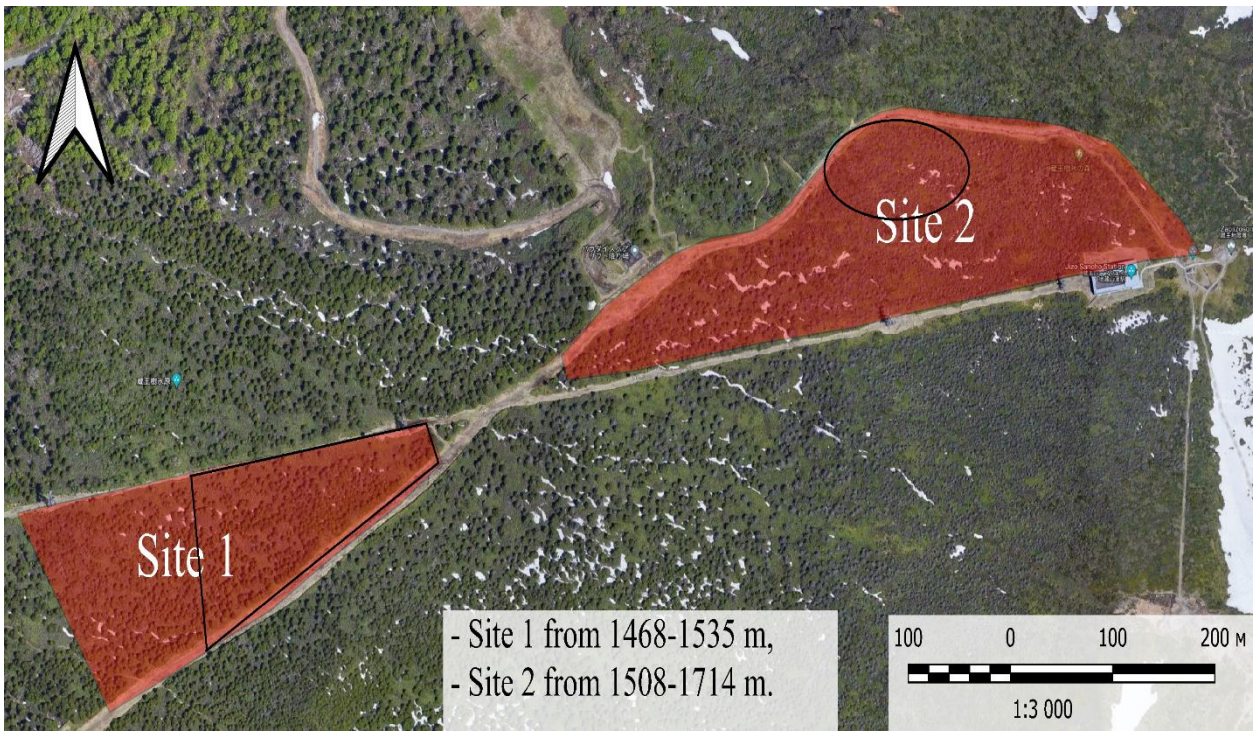
Response: Thank you for pointing this out. We will revise the sentence for clarity. The revised sentence will read as follows:

In addition to tree-ring width measurements, stable carbon isotope analysis of individual rings is a powerful method for assessing environmental impacts on tree physiology.

L129. Please add location of meteorological station. It would also be beneficial to mark where trees were sampled

Response: We have revised the manuscript to specify that climate data were obtained from the Zao Ropeway meteorological station, located at 1,661 m a.s.l. (coordinates approx. N 38° 09′, E 140° 26′), adjacent to the upper study site.

To improve spatial clarity, we have added a schematic site map indicating the distribution of sampling plots along the elevational gradient in the Zao Mountains. Furthermore, in the revised version of the manuscript, we plan to include more detailed geolocation data for each sampled tree by health category. We believe these additions will significantly enhance the transparency and reproducibility of our study.



L138-141. Does not belong in site description

Response: We agree that this sentence, which outlines the integrative approach and broader objectives of the study, is more appropriate in the Introduction rather than in the Methodology. We will amend the text accordingly.

L144. From which direction were core taken and/or direction of the slope?

Response: Thank you for your question. Tree cores were taken from the west-facing side of the trunk, maintaining a consistent orientation across all sampled trees. Coring was done perpendicular to the slope direction to minimize the impact of reaction wood on the tree-ring patterns. We will add this information to the revised manuscript.

L229. 4 trees per category were used for the TRI?

Response: No, twenty individual trees per health category were used for the TRI analysis. Each tree was represented by a single core, which is a common and widely accepted practice in dendrochronology when the sample quality is high and cross-dating is robust. The selected trees had well-preserved, complete cores, allowing reliable cross-dating and subsequent TRI calculation. We will revise the manuscript to clearly state the number of trees used per category for the TRI analysis.

L230. Please add the site description

Response: We will add a detailed site description to clarify the context. The dead trees used in this study were located at higher elevations, ranging from 1600 to 1714 m a.s.l., near the treeline. In contrast, the healthy and damaged trees were sampled at lower elevations, between 1468 and 1535 m a.s.l. This altitudinal difference corresponds to markedly distinct environmental conditions. The upper plots experience lower mean annual and growing season temperatures, stronger and more persistent winds, greater snow accumulation and longer snow-melting periods.

L232. It is assumed that all trees died in that year due beetle attack? How was the verified?

Response: Yes, it is assumed that all sampled trees died around 2016 due to the bark beetle outbreak. This was verified through consistent final growth rings dated to 2016 in all dead trees, based on visual cross-dating. Field selection focused on trees with similar decay stages and bark retention. Additionally, $\delta^{13}C$ values showed a marked decline starting in 2012 and remained low until 2016, confirming a physiological response consistent with infestation and supporting the estimated year of death. We will clarify this in the revised manuscript.

L240. Sample number is missing

Response: Thank you for your suggestion. While the total number of sampled trees (20 trees per health category) was described in the Methodology section, we agree that explicitly indicating the sample size in the figure would improve clarity. We will amend the figure accordingly.

L263. Sample number is missing

Response: Thank you for your comment. The figure presents $\Delta^{13}C$ records based on a subset of four selected trees pooled together for isotope analysis, with individual rings analyzed every five years. We will include this information to the figure caption to improve its readability.

L280. What analysis were done to prove «significant»

Response: This sentence will be removed.

L301: Is it the average annual wind direction distribution or for a season?

Response: Thank you for your question. The wind direction distribution described in the manuscript reflects the annual average wind direction distribution in the area.

L301. Are these the findings of the authors or from previous publications?

Response: The wind data were obtained directly from the Zao Ropeway Company, which operates weather monitoring equipment near Jizo Mountain. This facility provides continuous in situ measurements, which were analyzed by the authors specifically for this study and have not been previously published.

L322. Sentence implies that tree mortality was only due to climate

Response: We will modify the sentence to avoid any ambiguity.

L326. Please check sentence structure

Response: Thank you for pointing this out. We will revise the sentence to improve its readability as follows:

Thus, the case of Zao Mountain represents a rare instance of treeline recession. According to a meta-analysis by Harsch et al. (2009), only 1% of global treelines have shown a downward shift, while 52% have advanced upwards.

L329. Please add the site description

Response: Thank you for the comment. We will revise the manuscript to include the following site description:

The study was conducted at two distinct elevations in Zao Mountains. The lower elevation site (1468–1535 m a.s.l.) comprises relatively dense stands of *Abies mariesii*, occasionally mixed with other species, and includes the healthy and damaged trees. The higher elevation site (1600–1714 m a.s.l.) is located near the treeline and is composed almost entirely of *Abies mariesii*. This upper site includes the dead trees and is more severely impacted by the bark beetle outbreak. The two sites differ markedly in environmental conditions: the upper plots experience lower mean annual and growing season temperatures, stronger and more persistent winds, greater snow accumulation, and longer snow-melting periods. The average tree age across both sites ranges from 40 to 90 years.

L357. What analysis were done to prove «significant»

Response: This sentence will be changed to «The observed patterns confirm that dead trees experienced a sharp reduction in carbon assimilation before their demise, while healthy trees maintained stable physiological function.

L360. What would be a critical level. Please elaborate

Response: Thank you for the comment. In our study, we did not define a specific numerical threshold of $\Delta^{13}C$ as a «critical level» associated with mortality. We used the term «critical» in a qualitative sense, referring to sustained reduction in carbon assimilation that may compromise a tree ability to meet metabolic demands and initiate recovery. To avoid confusion, we will revise the sentence. The revised version will read:

Damaged trees showed some fluctuations in $\Delta^{13}C$ values, indicating physiological stress, although not yet reaching levels leading to terminal decline or mortality.