

Replies to reviewer's comments

Reviewer 1

The authors tackle a timely and relevant research topic, that is a driver analysis of tree mortality in Luxembourg across several years. The study is well written, the proposed methodology is cleanly executed, and the related work is reviewed in depth. The application of GAMs in this specific context is also novel.

However, there are two major methodological design concerns:

The authors report the vicinity of existing mortality to be the best predictor of new mortality, which is not a driver, as promised in the paper title.

1.1) Response: We appreciate the reviewer's thoughtful comment and partially agree with this assessment. We acknowledge that the spread of mortality is not a direct driver of tree mortality per se, but is tightly linked to it, as bark beetle infestations are often triggered or amplified by drought stress. To address this point, we have further elaborated this causal chain in the Introduction (l. 154-157).

We would like to retain the term driver, as it is commonly used in ecological studies to describe both direct and indirect influences on ecological processes. To avoid ambiguity, we explicitly defined its use in our manuscript accordingly: "In this study, environmental drivers are defined as biotic or abiotic factors that influence whether and where canopy mortality occurs under severe, multi-year drought conditions. Drought represents the overarching environmental setting and primary cause of mortality, while additional factors such as soil properties, topography, forest structure, and biotic interactions (e.g., bark beetle activity) modulate tree vulnerability and shape the spatial patterns of mortality.

The only covariate with relevant explanatory power was forest height. In the case of conifer trees, that bark beetles spread within some radius and do not normally travel cross-country as a random process is expected. Analogous, potentially for broadleaf, similar locations have similar trees in similar settings causing them to be potentially similarly susceptible to environmental stress. This raises the questions: "What makes a site vulnerable to initiating mortality versus experiencing spread?" or "Why does mortality spread in one region but not another?" if clustering is the only effect you observe. The currently chosen co-location variables might also already be somewhat representing the local conditions and overshadowing the actual drivers, e.g., slope, aspect, soil, etc.. It might make sense to attempt to drop mortality spread covariates in an additional analysis.

1.2) Response: Thank you for your comment. You have raised an important question as to why mortality might spread in some locations but not in others. In fact, we have considered the impact of different groups of drivers ("Mortality clustering and spread", "Forest structure" and "Topography") in the statistical results and have performed analyses in which groups of drivers were dropped during the calculation of partial R^2 values, also including those concerning spreading mortality (See figure 5). The explanatory value of the other drivers did not increase when dropping the group "Mortality clustering and spread", hence we do not consider this effect as dominant and overshadowing the other drivers. We have provided more information on this in the Results (l. 293 ff.) and Discussion (l. 389 ff.) sections.

Please discuss the impact of different model performances and thus map accuracies of broadleaf (F1=46%-52%) vs conifer (F1=72%-75%) (Schwarz et al., 2024) on the results, especially given that 71% of the studied forest is broadleaf. The implications also depend on precision vs. recall, which I was not able to extract from the previous study.

1.3) Response: Thank you for raising this point. The F1-scores reported in Schwarz et al. (2024) reflect the spatial agreement between the CNN model results and user-delineated testing data, and thus represent a conservative estimate of accuracy. Both classes performed well in terms of overall visual and structural agreement with the reference data.

Nevertheless, we acknowledge that lower F1-scores in broadleaf stands, which cover most of the study area, may have led to under-detection of small or diffuse broadleaf mortality patches (lower recall) and/or higher false positives in heterogeneous canopies (lower precision). Either bias could reduce the potential importance of the tested drivers in broadleaf forests relative to conifers. We have discussed this limitation in the manuscript in a new chapter (4.4 Study limitations, l. 470 ff.) to clarify that a weaker statistical signal in broadleaf forests may potentially reflect detection uncertainty rather than ecological differences alone.

Minor:

- Line 87: I'd suggest sticking to the wording "landscape-scale". Countries are only a political structure and heavily vary in size.

1.4) Response: We have changed the sentence to: „Recent advances in big data science, including increased computational power and the rise of artificial intelligence, now make it possible to address these data gaps by facilitating the acquisition of high-resolution canopy-level mortality data across landscapes (Cheng et al., 2024; Junttila et al., 2024; Schwarz et al., 2024).“ (l. 92 ff.)

- Line 125: Please reference Figure 2a earlier. Without the figure, the described binarization process is very difficult to understand.

1.5) Response: We have moved the first mention of Figure 2a to line 142.

- Line 125: How exactly is the centroid of the dead canopy polygon computed? In the naive way, i.e., $(\max X - \min X)/2$, $(\max Y - \min Y)/2$, this point can very easily land outside the actual deadwood polygon, e.g., with L-shaped polygons. This is especially important since this appears to be a semantic segmentation and not an instance segmentation mask.

1.6) Response: We used the standard QGIS Centroid tool, which uses the barycenter of the polygon and can occasionally place centroid points outside the polygon for irregular shapes. We have explained this in more detail in the revised manuscript in l. 143-145. We identified these cases (using inverse selection by location) and manually adjusted the points toward the approximate center of the polygon. We will add the following clarification to the manuscript: “Centroids that initially fell outside their respective polygons due to irregular shapes (e.g., L-shaped units) were identified and manually repositioned to a central location within the polygon.”

- Line 143: Are these distances calculated between the above-defined centroids or between polygon edges?

1.7) Response: The distances were calculated between the centroid of the dead canopy in 2020 and the polygon edge of the corresponding dead canopy in 2017 or 2019 as we did not calculate centroids for previous years. We have added the explanation to the manuscript in line 173 ff.: „We derived the distance to previously dead polygons by calculating the minimum distance from the closest edge of a dead polygon in 2019 (distance_2019) to the data points (centroids) in 2020 using the “Join attributes by location” tool in QGIS. We repeated this procedure for 2017 (distance_2017) to evaluate whether the location of dead polygons prior to the drought influenced mortality during the drought.“.

- Line 160: How accurate is Lis-L at detecting forest roads? This is a non-trivial task and the displayed polygon in Figure 2 appears fairly coarse, suggesting that (small) forest roads might not be captured. This might also explain the high correlation between both variables.

1.9) Response: Korzeniowska (2020) do not report a quantitative accuracy assessment for the road classification in the Lis-L data set. However, based on visual inspection and comparison with official road network maps, major and rural roads including those traversing forested areas are well represented. In contrast, small forest tracks and agricultural access roads are not captured by the data set. This limitation may indeed contribute to the observed correlation between road proximity and forest edge metrics, as fine-scale forest fragmentation caused by minor roads is not explicitly resolved. We have clarify the level of road representation and its implications for our analysis in the revised manuscript in the methods (l.200-201) and discussion sections (l. 418 ff.).

Figure 2 does not display forest edges created by roads. Instead, it shows the boundaries between different forest stand types (e.g., coniferous vs. broadleaf). For clarity, we chose to illustrate only a single coniferous stand polygon in this example and omitted adjacent forest polygons.

- Figure 3: Why is the colorbar scaled the way it is?

1.10) Response: The colourbar was square-root-transformed to best represent the distribution of values. A normally-distributed scale would have led to too small values not being visible well in the plot, leading to a relatively uniform colour in the broadleaf plot. We have modified the Figure caption accordingly (l.271-272).

- For readability, I'd replace "dist_e" and "dist_r" with "Distance_Edge" and "Distance_Road", and similarly for dist_19, ...

1.11) Response: We have replaced the abbreviations accordingly throughout the manuscript, including the figures when applicable.

- I think it is called "deadtrees.earth" and not "deadtrees.org".

1.12) Response: Great catch! We have changed the name. Thank you for pointing it out.

Suggested additional citations:

- Line 30: Most recent study supporting this: "Gazol, A., Pizarro, M., Hammond, W. M., Allen, C. D., & Camarero, J. J. (2025). Droughts preceding tree mortality events have increased in duration and intensity, especially in dry biomes. *Nature Communications*, *16*(1), 5779."

- Line 87: - "Cheng, Y., Oehmcke, S., Brandt, M., Rosenthal, L., Das, A., Vrieling, A., ... & Horion, S. (2024). Scattered tree death contributes to substantial forest loss in California. *Nature Communications*, *15*(1), 641."

- "Junttila, S., Blomqvist, M., Laukkanen, V., Heinaro, E., Polvivaara, A., O'Sullivan, H., ... & Peltola, H. (2024). Significant increase in forest canopy mortality in boreal forests in Southeast Finland. *Forest Ecology and Management*, *565*, 122020."

1.13) Response: We appreciate the suggestions for literature. We have read the papers and added the citations to the revised manuscript.

Reviewer 2

The author's work addresses an important topic of drivers of drought-induced tree mortality at the country scale (Luxembourg). The study is well written, and the results are supported by appropriate figures. However, there are several major points regarding the data selection and their corresponding methodologies that need clarification before publication.

Major points to clarify:

The advantage of using high-resolution (sub 1 m) data compared to freely available data, such as Sentinel-2 and Landsat is not clearly stated. Especially, as the authors do a large-scale country-wide study, Sentinel-2 could already have sufficiently high resolution to observe patterns, and the results would be less noisy. Additionally, more frequent acquisitions would be possible.

2.1) Response: The orthophotos used in our study are freely available from data.public.lu Our choice of very high-resolution data is based on two considerations:

First, as described in detail in Schwarz et al. (2024), the mortality data set was generated using a Convolutional Neural Network trained on 20 cm px⁻¹ orthophotos to automatically map canopy mortality across Luxembourg. This resolution was necessary to distinguish coniferous and broadleaf tree canopies based on fine structural features, which cannot be resolved by Sentinel-2 or Landsat. These fine structural features visible in the orthoimages allow a much more precise detection of dead canopies, reducing background scatter e. g. from browning of under-story vegetation.

Second, because the mortality data is available at such a fine scale, we took the opportunity to analyse canopy mortality using environmental drivers at comparable spatial detail (50 cm px⁻¹). Our objective was to investigate fine-scale processes, such as stand structure, bark-beetle infestation and spread, and local topographic context, that are likely not detectable with 10–30 m satellite imagery. Coarser satellite pixels mix live and dead canopy and therefore obscure early, localized, or small-patch mortality. Using very high-resolution data allows us to link individual canopy or small patch mortality directly to high-resolution drivers and to evaluate whether such fine-scale mechanisms aggregate into consistent landscape-scale patterns.

We have restated this reasoning more explicitly in the revised manuscript, adding to the Methods (l. 131ff. and l.161 ff.).

I do not understand why the bark beetle distribution and patches of already dead trees are used as an environmental driver for drought-induced mortality. I agree that bark beetle infestations can happen more often after trees are already damaged by a drought, but the beetle itself is not a driver for drought-induced mortality.

2.2) Response: We thank the reviewer for this important comment. We fully agree that bark beetle infestations are not the direct cause of drought-induced mortality; rather, they are often triggered or amplified by drought-stressed trees. However, in ecological studies it is common to consider both direct and indirect factors influencing mortality when defining “drivers.” In this context, the presence of bark beetles or nearby dead trees acts as a mediating biotic mechanism that can substantially influence the probability and spatial pattern of additional canopy mortality following drought (see also Response 1.1 to Reviewer 1).

To make this explicit, we have revised the manuscript to clarify the causal chain: drought acts as the primary driver, weakening trees, while bark beetle activity constitutes a secondary, biotic driver that mediates mortality under drought stress. We have also more clearly defined “drivers” in the manuscript as follows:

“In this study, environmental drivers are defined as biotic or abiotic factors that influence whether and where canopy mortality occurs under severe, multi-year drought conditions. Drought represents the overarching environmental setting and primary cause of mortality, while additional factors such as soil properties, topography, forest structure, and biotic interactions (e.g., bark beetle activity) modulate tree vulnerability and shape the spatial patterns of mortality.” (l. 154 ff.)

And “Bark beetle dynamics act as environmental drivers that influence where canopy mortality occurs under drought by shaping the spatial spread and clustering of mortality. In this study we characterised this driver using three groups of proxy variables defined as follows: i) “Distance to previously dead canopies in 2017 and 2019”, ii) “Distance to closest (other) dead canopy in 2020”, and iii) “Change in dead canopy area”.” (l. 168 ff.)

I assume that meteorological factors such as temperature and precipitation also play a major role in the drought-induced mortality, but no climatic variables are discussed in this study. Is there any temperature and precipitation data, or other climatic data available to examine local patterns that could also correlate with the drought-induced mortality?

2.3) Response: We thank the reviewer for raising this point. Indeed, climatic factors such as temperature and precipitation are key determinants of drought-induced mortality. In this study, however, our focus was on fine-scale, spatial drivers of canopy mortality, and the data we analysed are high-resolution in space but limited in temporal frequency. Climatic drivers, in contrast, operate over broader spatial and higher temporal scales, which makes it challenging to link them directly to individual-tree or small-patch mortality in the current data set. For this reason, we treated drought as a background condition and assume that the entire study period experienced sufficient water stress to trigger mortality events.

We are planning a follow-up study that will explicitly integrate climatic variables, such as temperature, precipitation, and drought indices, to examine their contribution to local

patterns of tree mortality. We have clarified our rationale in the new chapter 4.4 “Study limitations” in the discussion (l. 483 ff.).

Please give more information about the used data, such as the data source, sensor type, resolution, date/year of acquisition. This could be done, e.g., as a table at the beginning of the Methods section.

2.4) Response: Thank you for this suggestion. We have added a table in the Supplementary Material (Table S1), but are willing to move it to the Methods if preferred. The table summarises all data sets used in this study, including data source, sensor type, spatial resolution, and year(s) of acquisition. It is referenced in line 129.

Minor:

35 Can you give examples here of what you understand by abiotic/biotic factors?

2.5) Response: In the context of our study, abiotic factors primarily refer to environmental and topographic variables (e.g., slope, aspect, soil texture), whereas biotic factors include forest structure and bark beetle spread. We have replaced the word “factors” with “drivers” to be more consistent and added examples in the introduction to clarify these categories: “Beyond drought as the primary stressor, spatial variation in tree mortality is further shaped by interacting abiotic conditions (e.g., topography, soil properties) and biotic processes (e.g., forest structure, insect outbreaks), which act as environmental drivers of tree vulnerability and mortality. The complex interplay of these elements makes projections of future forest dynamics challenging.” (l. 37 ff.)

47 How do topographic variables differ from abiotic factors, or are they the same?

2.6) Response: As stated in the above response topographic variables would be considered abiotic factors, which we have replaced with “drivers”. We think that adding the before mentioned sentence clarified this sufficiently.

75 What do you understand as "high-resolution" canopy data? You mention Landsat data, but could you also use 10 m Sentinel-2 data for your analysis?

2.7) Response: In our study we operate on the level of 50 cm px⁻¹ as stated in line 101. The original resolution the dead canopy data was acquired at was 20 cm px⁻¹. This was necessary for the CNN model to differentiate between conifer and broadleaf canopy structures. We have stated the resolution in the revised manuscript more prominently now (l. 131 ff.).

In principle, 10 m Sentinel-2 data could be used to analyse canopy mortality at broader spatial scales. However, such an approach would require additional calibration and validation, and would be associated with higher uncertainty due to mixed pixels and the limited ability to detect small or early-stage mortality patches (see Schiefer et al. 2025). We have discussed this topic in chapter 4.4 l. 491 ff. In the revised manuscript.

87 If you are interested in understanding the mortality drivers at the landscape scale, why is it necessary to look at individual trees?

2.8) Response: Thank you for the question. Our approach explicitly links fine-scale processes to landscape-scale patterns. By analysing canopy mortality drivers at this fine-scale, but broad spatial extent, we sought to identify localized mechanisms, such as stand structure, or fine scale topographic differences. Exploring these signals across the landscape then allows us to test whether the drivers identified at fine scales remain consistent when applied to a heterogeneous, country-wide setting. To our knowledge this is the first study concerning tree mortality following such an approach. In our view, this ability to upscale process-based insights is a key strength of the study. We have made this reasoning more clear in the revised manuscript (l. 92 ff.).

95 From your hypotheses, the main aim of the paper is not clear to me. Can you link it more to the title of the paper?

2.9) Response: Thank you for pointing this out. The aim of the study was to identify and quantify the contribution of topography, forest structure and bark beetle spread in driving drought-induced canopy mortality across Luxembourg separately for conifer and broadleaf forests. We have revised the hypotheses as follows so that each reflects this aim more clearly.

“We hypothesized that drought-induced canopy mortality spread/patterns across Luxembourg is related to three main drivers:

- (1) Topography, with higher mortality expected on steeper and south-facing slopes,**
- (2) Forest structure, with taller stands and stands closer to forest edges exhibiting higher vulnerability, and**
- (3) Biotic interactions, where conifer mortality, but not broadleaf mortality, shows patterns consistent with bark beetle infestation and spread.” (l.105 ff.)**

108: How much of the whole country area is forest (in %). E.g., add it after the 900 km².

2.10) Response: Forests cover ~35% of Luxembourg's land area. We have added this to the revised manuscript as you suggested (l. 120-121).

139: 2.3.1 Why is the mortality occurrence and spread under "environmental data" and not under 2.2 where you describe the mortality data? I also do not understand why the distribution of the bark beetle patches is an environmental factor influencing the drought-induced mortality of other trees.

2.11) Response: Thank you for the comment. In our analysis, mortality occurrence and spread act as a driver because they influence mortality patterns during drought. For this reason, these variables were originally listed under “environmental data.” To avoid confusion, we have renamed this section to “Environmental drivers of canopy mortality” in the revised manuscript (l.153).

140: Is this the distance between the centroids (i.e. patchA_2017 to patchA_2019)? If your assumption of "spreading" is true, the distance between the centroids between the years would not necessarily change that much (for the same patches).

2.12) Response: You are correct that for patches already present in 2019, the distance between centroids may not change substantially from year to year. To account for the expansion or spread of mortality beyond existing patches, we also included the Δ area variable, which measures the change in size of dead-canopy patches between years. This allows us to represent both the influence of existing mortality and the growth of new mortality areas in our analysis. We have made this clearer in the revised manuscript (l. 181 ff.).

142: data point = centroid position?

2.13) Response: Data points refer to the centroids of dead-canopy polygons as well as the randomly distributed points representing alive trees, as illustrated in Figure 2. Please see also Response "1.6" to reviewer 1 on data points outside of centroids.

174: Why did you use northness/eastness instead of only one parameter "aspect"? Would this not be easier to interpret?

2.14) Response: Thank you for the comment. We used northness to assess the effect of slope orientation along the north-south axis, as south-facing slopes are often more exposed to drought stress. Eastness was included because stakeholders reported higher mortality on east-facing slopes, suggesting a potential influence along the east-west axis as well.

While aspect is intuitive, it is a circular variable (0–360°), which can complicate its inclusion in regression-based models and make statistical interpretation less straightforward. Aspect was transformed into northness and eastness to avoid circularity and enable its inclusion as linear predictors in the models. We have added a short sentence explaining this to the Methods section in line 215 ff.

239: I do not agree that no large-scale patterns are visible in Figure 3. In the coniferous forest, I see 2 "bands" of high mortality, and in the broadleaf forest, a North-South gradient.

2.15) You are, of course, correct. We have revised the wording in the manuscript to acknowledge the presence of regional gradients in canopy mortality and clarify our motivation for the subsequent fine-scale analysis. The revised text in line 281 ff. now reads:

"Regional gradients in canopy mortality were evident, including bands of elevated mortality in coniferous forests and a north-south gradient in broadleaf forests (Fig. 3). However, these broad-scale patterns alone do not fully explain mortality dynamics at the local scale. We therefore conducted a more detailed analysis of site-specific characteristics contributing to canopy mortality at a much finer resolution (50 cm)."

251: Where can I find these %-numbers in Figure 4?

2.16) Thank you for the question. The reported percentages ("Overall, the GAM models accounted for 44.7% of observed mortality in coniferous forests and 25.3% in broadleaf

forests.”) summarize the total explanatory power of the models. Figures 4 and 5 illustrate variable-specific effects and partial R^2 values, which contribute to this overall model performance. We have changed the wording in the manuscript to make that more clear. (l. 293 ff.)

266: ...this is not surprising given...

2.17) Response: Thank you, we have fixed this spelling mistake.

417 What about the large-scale patterns? Are they related to meteorological drivers?

2.18) Response: Thank you for this important question. Large-scale spatial patterns in canopy mortality are likely influenced by regional meteorological conditions, particularly the severity and timing of drought events. In this study, however, we focus on explaining within-country spatial variation in mortality using fine-scale drivers derived from very high-resolution data. Given Luxembourg’s relatively small geographic extent and the limited spatial variability of meteorological variables at this scale, climate factors primarily act in the background rather than as differentiating drivers of local mortality patterns.

Nevertheless, we acknowledge that the observed large-scale patterns may partly reflect underlying gradients in drought intensity or other climatic conditions. We have explicitly discussed this limitation in the revised manuscript chapter 4.4 (l. 483 ff.) and note that a follow-up analysis integrating satellite-based mortality time series with meteorological data is planned to more directly assess climate-mortality relationships across scales.

423 The authors do not discuss the influence of climate variables on the tree mortality.

2.19) Response: We thank the reviewer for this important comment. We fully agree that climatic variables such as temperature, precipitation, and drought indices play a fundamental role in drought-induced tree mortality. In this study, however, our focus is on fine-scale spatial drivers of canopy mortality derived from very high-resolution data, while the temporal resolution of the mortality observations is limited to annual data. Most climatic data sets, in contrast, have high temporal but relatively coarse spatial resolution, making it difficult to robustly link them to individual-tree or small-patch spatial heterogeneity of canopy mortality patterns analysed here. For this reason, we are treating drought as a background condition that is assumed to affect the entire study area during the analysed period, and focus on how local topography, forest structure, and bark beetle infestation modulate mortality under these conditions. We have clarified this rationale more clearly in the introduction (l. 100 ff.) and discussion (l.483 ff.).

We are currently planning a follow-up study in which the mortality data will be upscaled to a satellite-based time series, allowing for a more explicit integration of climatic variables and a detailed analysis of climate-driven mortality relationships across space and time.

Figures:

Figure 1: I think it would be easier to interpret if the pixel size is in km and the color in % forest area. Is it possible to color the non-forest areas in a different color than white? I find it hard to distinguish it from the color of the low forest area.

2.20) Response: Thank you for the suggestion. We have changed the figure according to your suggestions.

In L123, you write that you only use the “pure” forest sites >75% but some pixels are colored in both maps. Is this map still representing the mixed forest sites as well?

2.21) Response: Thank you for the clarification request. The maps display forest cover aggregated to a 1 km² grid. Although our analysis uses only homogeneous forest stands (>75%) from the LIS-L dataset, aggregating these stands to larger grid cells means that individual grid tiles can contain both coniferous and broadleaf forest types. As a result, the maps may show mixed forest composition even though only homogeneous stands were included in the underlying analysis. We have added our reasoning to the figure description (l. 112 ff.).

Figure 2: Please use another color combination. The red polygons over the forest image are not colorblind-safe.

2.22) Response: Thank you for this suggestion. We agree that the former colour scheme was not optimal for accessibility. We have revised Figure 2 using a colourblind-safe colour palette.

Figure 6: What does a negative deltaArea indicate? Would this indicate forest recovery, or can it also be that areas are no longer forest?

2.23) Response: A negative Δ area indicates a reduction in the mapped dead-canopy area between consecutive years. This can reflect vegetation recovery or canopy closure following disturbance. We have stated these possible interpretations in the discussion section of the revised manuscript (l. 430).

Figure 7: Add the *diste* and *distr* in the caption (L295).

2.24) Response: We have added *distance_edge* and *distance_road* in the caption to improve readability.

Figure 8: It should be “elevation”.

2.25) Response: We have corrected this spelling mistake.