Response to reviewer comments on “Storm damage beyond wind speed – Impacts of wind characteristics and other meteorological factors on tree fall along railway lines”.

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Preliminaries: We would like to thank the anonymous reviewers for their comments on our manuscript. We find the comments helpful and constructive. We think that they will help to improve the manuscript. In the following pages we set out in detail our responses to the comments and how we plan to act on them. Note: The line numbers given by us refer to the numbering of the track-changes file. We also decided to change the title of the manuscript to: Tree Fall along Railway Lines: Modeling the Impact of Wind and Other Meteorological Factors.

Review 1

I would recommend that the authors create a wider introduction discussing the limitations of using gridded rather than point observations which are particularly important for wind extremes including gusts and precipitation amounts.

Indeed, the reviewer is correct that wind speeds from reanalysis and from stations are not the same. However, the ERA5 reanalysis data is found to be well correlated with station data. The occurrence of large scale winter storms is also well represented in the reanalysis data, and so reanalysis have been used successfully for an estimation of storm damages to residential buildings. We have added remarks at several points in the text. We justify the selection of ERA5 as input data and point out its limitations in chapter 3.2 Meteorological data. We added the last sentence for a wider introduction:

> “The advantage of using wind speeds from ERA5 is the coverage of the complete area and period under investigation. For these reasons ERA5 and similar reanalysis products are already used as in put data in many forecast and impact models (Pardowitz et al., 2016; Valta et al., 2019; Battaglioli et al., 2023; Cusack, 2023). Previous versions of the ECMWF reanalysis have successfully been used to reproduce windstorm-related damage as recorded by the German Insurance Association (Donat et al., 2010; Prahl et al., 2015), suggesting the usability of these data in spite of deviations with local station measurements (Minola et al., 2020). Studies comparing wind speed observation with ERA5 reanalysis find good correlations(Minola et al., 2020; Molina, Gutiérrez and Sánchez, 2021).”

We also elaborate on the topic in the Discussion (line 615):

> „While evaluations of ERA5 gust speeds with observational data point out some limitations they also find the data in general to be a good representation of local measurements. Molina et al. (2021) compare hourly 10 m wind speed from ERA5 with wind observations from 245 stations across Europe. They find that „Most of the stations exhibit hourly [Pearson correlation coefficients] ranging from 0.8 to 0.9, indicating that ERA5 is able to reproduce the wind speed spectrum range [...] for any location over Europe". Minola et al. (2020) compare ERA5 with hourly near-surface wind speed and gust observations across Sweden for 2013–2017. They, too, find Pearson correlations of 0.8 and higher for daily maximum gust speeds. However, they do point out that „evident discrepancies are still found across the inland and mountain regions" and that higher wind speeds and gust speeds display stronger negative biases."

Additionally, ERA5 and other reanalysis wind data is used in many forecast and impact models (Pardowitz et al., 2016; Valta et al., 2019; Battaglioli et al., 2023; Cusack, 2023).

To point this out and further justify our choice we add the following sentence in line 188:

> "For these reasons ERA5 and similar reanalysis products are already used as in put data in many forecast and impact models (Pardowitz et al., 2016; Valta et al., 2019; Battaglioli et al., 2023; Cusack, 2023)"

The literature surveyed is rather limited/dated in terms of wind extremes.

We incorporated more recent literature on topics such as the development of highly resolved gust speed and air flow products or the tracking and classification of damaging storms. Please see our response to review 2 for more details.

Further the use of regression methods would be seen as rather simplistic/outdated compared to the use of some kind of machine learning or numerical modeling that can predict the variables and how they interact as well as being available on much smaller grid sizes.

Regression analysis is a well known standard approach, particularly suitable in terms of providing results that can easily be interpreted. It is also often used in tree damage modelling (as we point out in line 98). Machine Learning (ML) models are well fitted to provide accurate predictions from big and complex data sets. However, the distinction between ML and statistical models is not always precise and regression approaches can be seen as a version of ML for non-complex data. In our work we are not yet intending to build a complex ML model of tree damage factors, but contribute to the understanding of tree fall risk. The outcome shall aid in a later attempt to build a complex predictive tree fall model, something we are currently working on. For such a purpose statical learning approaches like regression modelling are beneficial as they are built for inference (unlike Machine Learning) and allow for a detailed examination of the variables and their relationships (Suvanto et al., 2019; Merghadi et al., 2020; Kumar and Vannan, 2021).

We do not understand how the reference to numerical models is meant. To our understanding numerical models rely on a set of mathematical formulas that explain the physical processes in a system. Thus, such a physical model is not suitable for our approach which explores statistical relationships.

In the outlook we point to the future use of the model which can be run with output from numerical weather forecasts and climate scenario runs.

Furthermore, the modelling approach can not change the grid size. The grid size of our model output is predetermined by the ERA5 data. The ERA5 dataset is a well established basis for estimating meteorological conditions, which allows an inter-comparability to other studies. There is, to our knowledge, no reanalysis dataset that is clearly more suitable and should thus be preferred.

On the other hand the application (tree damage) is not much published about these days. The real issue with the manuscript is the simplicity of the analysis coupled with the lack of presentation and interpretation of the results and lack of any validation. E.g. a map of relative tree fall probabilities in different regions might have been interesting or a discussion of how these vary by season or over time.

We do not understand what is meant by "lack of any validation". The model is trained and therefore validated with observed tree fall events. The validation process (10-fold crossvalidation and calculation of the Brier Skill Score) is described in in the Methods (line 240-252).

Figure 2 and 3 show variations in tree fall event over season and over time. We added a line to the Results (line 295) to include the Figures:

> "As can be seen in Figure 2 and 3, winter wind storms cause the highest daily numbers in tree fall event while very high monthly tree fall numbers occur from January to March, the season of winter wind storms. However, other meteorological predictors than wind speed caused by storms factor in to tree fall risk:"

As we only consider winter events in our model (see section 3.2) we cannot evaluate the model outcome for different seasons. In summer, other factors than in winter can play a role. This is left for future studies.

We agree that more detailed maps would be interesting. Unfortunately, due to data privacy agreements with our data provider we cannot publish maps of tree fall locations or local event probabilities.

The assessment that strong and prolonged winds coupled with high precipitation is surely already well-known (also by these authors) so the impact of this study seems rather limited.

To our knowledge storm length has not been used in impact models before and precipitation is rarely used in impact models. As we clarify in the Introduction the role of soil moisture and precipitation is not completely clear and a matter of discussion. As is stated in the review paper of Gardiner (2021): "The issue of soil moisture on tree resistance to uprooting is not totally clear with mainly indirect evidence to suggest that there is an increased risk with increased soil wetting […]. There have been very few direct measurements of the impact of differences in soil water on rooting resistance."

To elaborate on this we added to line 133 of the Introduction:

> "However, the role of soil moisture on tree fall risk is not completely clear and only few field experiments have been done on the topic (Gardiner, 2021). Both very wet and very dry soils

might have a negative impact. The legacy effects of drought may cause lasting changes in tree physiology and weaken the tree (Kannenberg, Schwalm and Anderegg, 2020; Zweifel et al., 2020; Haberstroh and Werner, 2022). Therefore, droughts are expected to increase damage caused by wind (Gardiner et al., 2013). Yet, Csilléry et al. (2017) found both positive and negative effects on tree damage. They suggest that in some stands drought weakens the trees and makes them more vulnerable to wind loading while in others dry soils make them less vulnerable towards overturning. "

The simple line plots showing how probabilities vary or how the interaction terms impact the results are very simple. It is difficult to believe that these 10 regression terms are independent or that this kind of analysis should not have to be validated in some way e.g. by comparison with data or numerical modeling so addition of further analysis should be required to enhance the utility of this work.

Meteorological predictors used in impact modelling are rarely completely independent, there is usually some correlation. The question is: Is such a correlation critical? In the Methods (line 277 to 278) we explain how we use the VIF to test if this correlation of the predictors, the so called multicollinearity, is too high. Our test criteria shows that there is no critical multicollinearity.

As we already stated above, the model is trained on observed tree fall events and 10-fold cross validation is used to calculate the predictive skill of the model (see Methods).

In the outlook we point out how we plan to use the model with output from numerical climate model runs to explore developments in future climate scenarios.

Review 2

Thank you for the interesting, improved manuscript about Storm damage beyond wind speed – Impacts of wind characteristics and other meteorological factors on tree fall along railway lines. It is valuable to do case studies and develop methodologies. We need these very much. It is important to develop new models that can be tested in other countries and other cases.

I do, however, have some concerns that I wish to share next (regarding the track changes version):

The paper is interesting as such. It has 45 research papers cited from the field of forestry/biology/ecology. It has 16 papers from the field of meteorology and some of them are climatological as well. There are statistical references, data references and some engineering references. Considering the meteorological world, I find the references not to be in balance with the weather and climate impact research already conducted. Thus, I aim to highlight what I believe is still important to improve:

Thank you for your insightful criticism and suggestions, especially for the literature suggestions. We added the recommended literature as well as additional references to the respective sections in the Introduction as well as the Discussion. Please see our further response for details.

<u>Minor revisions:</u>

The lines 324-325 could be clarified, it would help some readers.

• What does it mean that the study investigates long-term and large-scale storm damage modelling? Especially what is long-term in this context?

To make this point clearer we rearranged the introduction (see our next response) and changed this statement in the following way:

> "Many impact studies focus at singular and very damaging storm events (Hale et al., 2015; Kabir et al., 2018; Hart et al., 2019; Hall et al., 2020; Zeppenfeld et al., 2023). Those who study longer time periods are often focused on small areas such as experimental plots (Albrecht et al., 2012; Kamimura et al., 2016) or smaller administrative units (Jung et al., 2016). In this study, we try to contribute to this ongoing research with using data covering a large area over several years (2017 to 2021) and exploring the impact of different meteorological factors."

I find the discussion part still not ready.

Lines 350-352 state that there is not much research on various meteorological parameters on forest damage. The statement is biased and that could be because the citations are mainly from the field of forestry, ecology and biology. A more careful wording would help the reader to understand where the gaps are.

Please:

• indicate the gaps within forest research concerning impact assessments of meteorological conditions,

• give a bit more credit to the meteorological community for their work related to impacts on forests.

Within the climate impact and weather impact research community, it is trivial to combine several parameters and look for the reasons for the impacts of extreme phenomena, they do in with the past climate and then assess the future.

In the discussion section, you could aim to clarify and focus the discussion on the most important topics and also still add some relevant literature. Here are some examples that you could also cite:

• Line 419. Venäläinen et al. 2020 discusses the compound risks, wind and snow loading. Drought among other things is also essential. Climate change induces multiple risks to boreal forests and forestry in Finland: A literature review https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.15183

• Lines 428-429. Lehtonen et al. 2019 Projected decrease in wintertime bearing capacity on different forest and soil types in Finland under a warming climate https://hess.copernicus.org/articles/23/1611/2019/

• Lines 335-339: a reference to the paper Valta et. al. 2019 https://doi.org/10.5194/asr-16-31-2019.

Valta et al. 2019 presented a method to assess tree fall risk with forest damage/tree loss data, winddirection data and wind strength. It also discussed the soil issues. It discussed how important it is to communicate the risk in an understandable way.

• The review report on storms and storm impacts in the past and future may also help you Gregow et al. 2020 https://helda.helsinki.fi/server/api/core/bitstreams/57cd106d-d6d9-495c-973a af4e6f3ce222/content

In the discussion section, it would be better to write if there are research gaps within the field of forest management and forestry, and what specifically this paper aims to solve:

• It is true that within the disciplines there is a lack of cross-disciplinary understanding, applicability of datasets, development of impact models and indicators that are replicable and exploitable in a wider region. That would be worth discussing. Why do we need national investigations? Why are they not always applicable to other regions but still are worth conducting?

The paper could point out how rather sophisticated research has been done within the meteorological community and what was already done for the rail infrastructure. E.g., there is a lot of research on investigations into storm tracks, dynamical impact modelling with weather models with storm cases, within the field of attribution research regarding impact of climate change on storms and their impact on society.

Maybe also this classification paper would worth to know EGUsphere - Classification of North Atlantic and European extratropical cyclones using multiple measures of intensity (copernicus.org).

Maybe you could highlight the following in some sophisticated way: is it so that the meteorological research conducted is not easy to employ within the discipline of biology, ecology and forestry due to the difference in scale, operational data flow, measurements? And, that there is not enough impact data available to improve the impact models and you need to consider carefully how to combine the relevantparameters and this is what you aimed to do now to have consistency with the rail risks and future studies?

Also, one issue is that researchers may not have open access journals to read in all disciplines, thus we keep on working in silos. For instance, here the aim is to specifically help the traffic sector, and the tailoring of the research is conducted based on that request but still you need to understand ecology, forest and forest management, geography and soils, rail management, seasons, climate and meteorological datasets and then it is already complex.

Many thanks for these helpful comments. To address these issues we changed the text in the following ways.

We rearranged the Discussion and added theses general remarks to the top of section 6 and removed the first paragraph of section 6.1 (which we renamed Model Building and Predictor Selection):

> "There is a vast number of studies which contributed significantly to understanding storm impacts on forests, particularly in areas such as impact modelling (Gardiner et al., 2008; Hale et al., 2015; Kamimura et al., 2016; Valta et al., 2019; Costa et al., 2023), wind climatology (Gregow et al., 2017; Mohr et al., 2017; Jung and Schindler, 2019; Tervo et al., 2020) or field campaigns and pulling experiments (Kamimura et al., 2016; Kamo et al., 2016; Schindler and Kolbe, 2020). A key goal of these research efforts is to develop functional forecast models which can predict tree and forest damage. Such a model should be applicable to major tree species, diverse landscapes, and various forest types. It would help to identify areas of risk, estimate damages in future climate scenario or during possible most extreme events and asses management strategies for foresters and infrastructure providers like the Deutsche Bahn (Akay and Taş, 2019; Albrecht et al., 2019). However, there are several hurdles on the way to this goal: 1. There is a lack of damage data covering large areas and longer time periods which is needed to train these models and often a lack of environmental data to feed into them (Hart et al., 2019; Maringer, 2021). 2. There is also a lack of highly resolved gust speed data. Such data is needed to fully understand and model tree damage ((Jung and Schindler, 2019; Gregow et al., 2020). 3. Many of the existing studies focus on a partial aspect of the issue for example on a small spatial region, a single damaging storm event or one tree species (often due to the lack of bigger data). 4. And finally such a model would need to incorporate parameters from many relevant fields (such as tree biology, forestry, meteorology, fluid dynamics, pedology and others) as well as their interactions. So far, many studies focus on the parameters from their respective fields. These issues make it difficult to apply existing works to different tree species or forest types and also to use the existing impact models on data from climate models. Several works call for more impact data and longer time series, addressing the interaction of multiple risks and for inter-disciplinary approaches and cooperation (Valta et al., 2019; Gregow et al., 2020; Venäläinen et al., 2020; Gardiner, 2021). Additionally, there is ongoing work dedicated to developing more accurate small-scale gust speed products (Primo, 2016; Schulz and Lerch, 2022).
>
> In the field of forest impact modelling many models focus on biological and environmental predictors such as tree, stand and soil properties (Mayer et al., 2005; Schindler et al., 2009; Kamo et al., 2016; Kabir, Guikema and Kane, 2018; Díaz-Yáñez, Mola-Yudego and González-Olabarria, 2019; Hart et al., 2019; Wohlgemuth, Hanewinkel and Seidl, 2022). Meteorological predictors like precipitation or soil moisture are considered less often (Schmidt et al., 2010; Hall et al., 2020). Wind is mostly considered as mean or maximum wind speed (Hale et al., 2015; Morimoto et al., 2019; Hall et al., 2020). This focus on environmental predictors and mean wind speeds is often also true for studies that consider tree fall on railway lines (Bíl et al., 2017; Kučera and Dobesova, 2021; Gardiner et al., 2024).

Many impact studies focus at singular and very damaging storm events (Hale et al., 2015; Kabir et al., 2018; Hart et al., 2019; Hall et al., 2020; Zeppenfeld et al., 2023). Those who study longer time periods are often focused on small areas such as experimental plots (Albrecht et al., 2012; Kamimura et al., 2016) or smaller administrative units (Jung et al., 2016). In this study, we try to contribute to this ongoing research with using data covering a large area over several years (2017 to 2021) and exploring the impact of different meteorological factors. In a next step, our model can be applied to gridded climate model data to estimate risks for trees in future climate scenarios.

We focused on different types of meteorological predictors, including those that describe wind characteristics, but also predictors describing precipitation and soil conditions. We showed that meteorological predictors other than mean or maximum wind speed have a significant effect on tree fall risk and improve the models predictive skill."

We also added this section to the Introduction (line 92) to give more credit to meteorological research:

"One issue the field of tree and forest damage modelling faces is the lack of highly resolved gust and air-flow data. Great efforts are being made in recent years in developing small-scale gust speed products which can also be used for impact modelling (Primo, 2016; Albrecht, Jung and Schindler, 2019; Schulz and Lerch, 2022). Additionally, there are a number of studies that identify, track, and classify the storms most damaging to forests and infrastructure (Gregow et al., 2017; Mohr et al., 2017; Jung and Schindler, 2019; Tervo et al., 2020)."

Line 443:

~~"One would assume the trees adapt to this and thus wind direction would have either no effect or that easterly winds would increase tree fall risk (Bonnesoeur et al., 2016)"~~

"It is assumed that trees adapt to the dominant wind direction and that untypical wind directions, in this case easterly winds, increase tree fall risk (Bonnesoeur et al., 2016; Valta et al., 2019)."

Line 471:

"The influence of precipitation and soil moisture on tree fall during winter will likely increase in northern forest. Here rising temperatures and shortened winter decrease soil frost and thus root anchorage (Gregow et al., 2017; Lehtonen et al., 2019; Gregow et al., 2020; Venäläinen et al., 2020)."

Line 485:

"The role of droughts for other hazards such as fires or bark beetle infestation is well studied (Venäläinen et al., 2020; Singh et al., 2024). However, research on the impact of drought on wind induced tree damage are inconclusive."

Line 604:

“In the data set about 25% of tree fall events occur at maximum daily gust speed below 11 m/s. These tree fall events might be caused by processes unrelated to meteorology. Valta et al. (2019) points out that individual tree fall is already possible at low wind speeds such as 15 m/s. Events at even lower speed cannot be ruled out. On the other hand, these events might be related to wind events not resolved by the ERA5 reanalysis and thus caused by wind speeds that were higher in reality than shown in the data.”

Please discuss more about the needed elements:

• Especially lines 345-354 read, as if there was not much research done within that field yet. In Germany there is a start with development of tools too and there is a will to develop safety. Lines 357-364 explain the status, and how this research conducted now brings new results to the field. You could emphasize this a bit more.

It was not our intention to belittle existing research. It is true that there is already a lot of research. However, we wanted to point out that many of the existing impact models focus on biological and environmental predictors and do not incorporate many meteorological predictors. By changing the Discussion as stated above we hope we could make this clearer.

• Maybe you could skip lines 374-376 and concentrate what it is that you specifically found as new and applicable in Germany.

We removed these lines.

• Lines 399-401 should be merged to be part of some other chapter and not separate as they are now.

We removed these lines as the point is already made clear at the start of the Discussion and in the Conclusion.

• Lines 547-549 are not finalized yet, please do cross-check.

We cannot identify the issue. Maybe there was a mix-up with the line numbers?

Good progress:

• Additions on lines 515-519 and 595-598 are very good.

References

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