Reply on RC1

Introduction:

1. - L52-53 The introduction lacks some literature that links precipitation to tree falls (this linkage might be obvious for gravitational mass movements and floods). Does the year 2021 really proofs this relationship? Isn't it likely that the heavy rain was accompanied by wind gusts? *There are only limited number of studies on precipitation induced tree fall events available. This is mentioned in the discussion section (lines 419-421). If the editor wish, we can add the literature to the introduction section. We agree with the reviewer that heavy precipitation events are often accompaigned by wind gusts so it is difficult to separate clearly what the cause of the tree fall event was. Nevertheless, the influence of soil moisture on the stability and vitality of trees has been proven in various studies (e.g. Usbeck et al. 2010; Hanewinkel et al. 2011; Lucia et al. 2018; WindtrhowHandbook for British Coulmbia Forests 1994).*

Datasets:

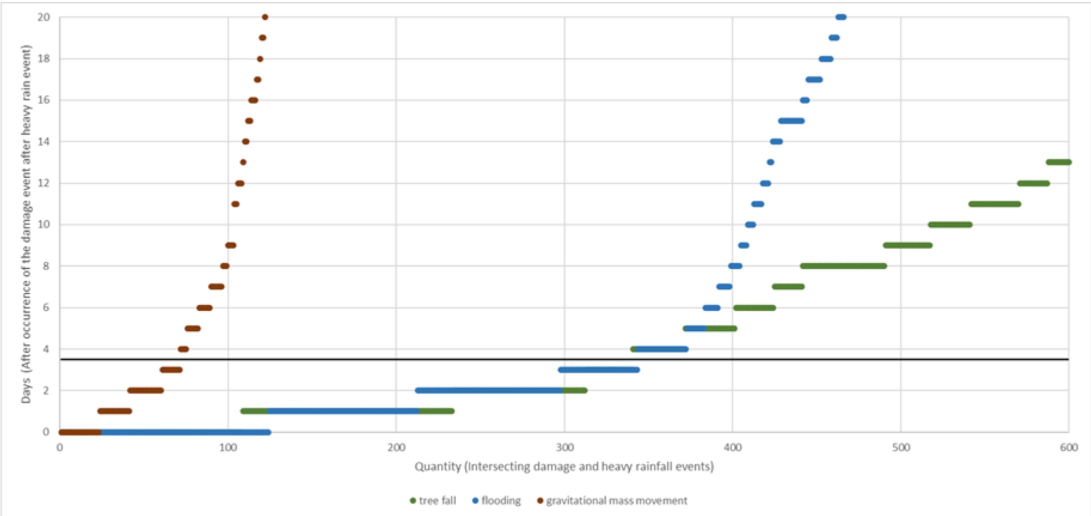
1. - L79 spatial intersection has not been explained yet. At least a reference to the section where it will be explained is needed. *We can add a paragraph describing the spatial intersection in detail in the revised manuscript: "The spatial and temporal intersection of the heavy rainfall events and damage events along the railway was carried out by intersecting the CatRaRE polygon data provided by the DWD and the compiled railway damage databases. First, the spatial intersection was carried out using the GIS software ArcMap, version 10.8.1. In ArcMap, the respective damage events tree fall, gravitational mass movement and flooding, which are available as point information, were intersected with the CatRare heavy rainfall events (W3-catalogue) between 2011 and 2021, which are available as area polygons, using the tool "Spatial Join". In the processing options of the Spatial Join tool, the connection process "Join one to many" must be selected so that multiple join features (heavy precipitation events) can be assigned to each target feature (damage event). This creates a database in which all spatially overlapping heavy precipitation events are assigned to the damage events."*
2. - L93-100 spatial intersection should be explained first. This paragraph should be moved into the results section. It is no longer a description of CatRaRE. *We can move this section into the results section.*
3. - L136 Why 5km resolution and not 1km (HYRAS-DE-PRE)? Are you aware that daily precipitation in HYRAS is aggregated from 06 UTC to 06 UTC and that a clear assignment to a single date is not possible? Is daily precipitation the explanatory control variable or 30-day antecedent precipitation (L193), or both? A list of all explanatory control variables is needed in this section (not only a description of the raw data that was used to derive them), otherwise it becomes confusing. *We will add a table with descriptions of all explantory control variables (see reply to comment 5.). The resolution of the HYRAS data used was 1 km x 1 km, unfortunately the stated resolution of 5km x 5km came from a mixup in the documentation of datasets tested and used. With regard to the time period aggregated we assumed that even despite the time discrepancy the precipitation is still representative for 75% of the day in question. To confront this problem, a variable that represent longer time periods before the event (30-day antecedent precipitation) where also included in the analysis as explanatory control variable.*

4. - L139 DWD soil moisture is based on observations and a soil moisture model. *We will add the information that DWD soil moisture is based on observations and a soil moisture model.*
5. - In general, I find it difficult to keep track/distinguish between the different terms (e.g. rain and rail events). A complete list or table in this section on how the terms are used and what they encompass would be helpful (event, natural hazard, observation, explanatory control variables). *In the revised version we will add a table explaining all the important terms. The table will look like this:*

Heavy rainfall event	Warning Level W3 (events with 25-40 l/m² in 1 hour or 35-60 l/m² in 6 hours)
Rail / damage events (tree falls, gravitational mass movements, flood events)	Damages recordes by DB Netz AG; resulting from a damage database of DB Netz AG
Damage database	Damage database of DB Netz AG in which the damage events along the railway lines are listed
Natural hazard	In this context: tree falls, gravitational mass movements, flood events
Natural hazard event datasets	Individual datasets of each natural hazard resulting from the damage database of DB Netz AG
Track section (railway)	Defined by the GIS-layer "geo-strecke" provided by DB Netz AG. According to this layer, the German rail netork is divided into 15939 track sections.
Route segment (railway)	A section of the German rail network between two adjacent operating points. The total length of the German rail network owned by DB is 56939 of tracks km, which is divided into 9679 route segments. The segments differ in length between 140 m and 12.7 km with an average length of 3.4 km.
Explanatory control variables	Climatological and hydrometeorological variables related to the investigated natural hazards to check for other relationships in the statistical regression analysis. Variables used in this study are: daily precipitation, daily soil moisture and hazard indication map for slope and embankment landslides.
Observation	Description within the statistical analysis methods for the size of the data set as a combination of days and route segments. The complete dataset is available for 3987 days (= time-series units) and 9679 route segments, resulting in a total of 38590173 route segment - day combinations. The number of observations used in the succeeding models vary depending on the available time period of the natural hazard event datasets.

Methods:

1. - L156 I am not convinced. A flood can be the result of long-lasting precipitation that is not categorized as heavy (as can be seen this year in Germany and Britain). *We agree that long-lasting precipitation not categorized as heavy can trigger a flood. But it is not the scope of the sentence to describe triggers for flood events. The scope of the sentence is to define which heavy precipitation events will be regarded as possible trigger for secondary processes in this study.*
2. - L166 Please explain the analysis of natural breaks (in which data set?) and its results and how this supports the choice of the time period. *The paper already mentions that this methodology is used because there is no other scienitfically valid source on threshold values when precipitation can have an impact on the natural hazeads analysed. In the revised version, we can add an explanation and a figure on the natural breaks, either in the text or in the appendix, something like this: „This can be observed in Figure XY. In this graph, the days between the occurrence of the damage event and the heavy rainfall event are plotted on the Y-axis and the number of overlapping events for all three types of damage are plotted on the X-axis. The black line after 3 days difference marks the limit used in our analyses and clearly visible in the data, up to which a connection between heavy rain and damage event can be established. It is well visible that for all event types up to day 3, a large number of damage events can be linked to a heavy rain event that occurred immediately before. From day 4 onwards, this link decreases considerably, so that one can consider a natural break in the data, so that the heavy rain events that occurred more than 3 days before a damage event can no longer be clearly identified as the cause for the occurrence of the event. Due to this natural break in the data, which can be observed almost identically for all event types, this limit value of the difference of 3 days between the onset of a heavy rain event and the damage event is used in the further analyses."*



3. - L171 Corresponding to what? *„Corresponding" refers to the values from the explanatory control variables.*
4. - L174 Please explain what panel data analysis, cross sectional analysis and random-effects logistic regression are, for what kind of investigations they should be used and why you chose to apply them here. As these methods are mostly used in social and economic science. It shouldn't be assumed that the methods are known by the audience this article addresses (geological/physical/climatological scientists). I suggest to also write down the equations, explain all variables and terms in the equations using an example from this study. *We would suggest adding the following explanation at the beginning of the sections 2.2.3.1 and 2.2.3.2,*

respectively:

„For the evaluation of the datasets, panel data analysis was chosen as statistical method as it allows the analysis of two- or multidimensional panel data by running regression models over chosen dimensions. The method, originating in the econometrics, is used to observe and explore the relationships between observations of heavy rainfall and natural hazard damage events as the relationships may be very complex and the aim is to explore them further. The dimensions of the data collected for panel data analysis are typically covering the temporal and spatial dimension, here they are time and route segment with or without an event/observation as well as additional explanatory variables that take into account the heterogeneity of the studied individuals. The panel dataset has a matrix structure and includes observations and explanatory variables for each individual route segment for each day of the studied time period (Biørn 2017). The individual or in this case the route segment can be observed over a long time period and opposed to time-series and cross-section data, the effects of individual-specific variables as well as time-specific variables can be explored in a panel analysis. A typical panel data regression model is represented by the equation $y = \beta_0 + \beta_1 x_{ij} + \beta_2 \varepsilon$, *where y ist the dependent variable, x is the independent variable,* β_0, β_1 *and* β_2 *are coefficients and ε is an explanatory control variable, i and j are indices for the dimensions chosen for the analysis (e.g. time and space/individual). The limits of panel data analysis are determined by the data quality and consistency, distortions of measurement errors, short time-series dimensions as well as the relationship between the variables due to potential variable bias and unobserved nuisance variables which are correlated to the observable explanatory variables in the equation (Baltagi 2005; Biørn 2017).*

In this analysis, the authors were interested especially in the probability of which the natural hazard damage events occur in relation to the heavy rainfall events. This was modeled by employing a logit link function, the natural log of the probability that a natural hazard event occurs divided by the probability that it does not occur. Non-linear models are in this case more suitable for modeling binary responses (Wooldridge 2010). To account for the unobserved individual heterogeneity and characteristics (e.g. small scale topography and vegetation) of each route segment, where the damage and heavy rainfall events can occur, a random variable was introduced and a mixed random-effects model used for the estimation of the parameters."

„A cross-sectional analysis is employing a similar equation and logistic model as the panel analysis, but it aims at exploring the effects of one independent variable upon a dependent variable of interest at a certain point in time. This is done by using econometric methods to effectively hold other factors fixed. This approach is limited when the control variables are not completely considered and not measured with the same quality (Wooldridge 2010)."

5. Please homogenize the usage of indices. i is used for route segments, time lags and combinations of route segments with heavy rain events. This makes it difficult to understand the equations. *We understand that the usage of i as the index of choice in all equations may be confusing. We therefore suggest to replace the index for the number of days after heavy rainfall with „d" in equation 2, the route segment index with „r" in equation 3a and 3b, the index for observations of heavy rainfall events in equation 4 with „e".*
6. - L182 Single point in time (which point in time?) or rather all event time steps together? Please explain in more detail. *This sentence refers to the cross sectional analysis which indeed is only calculated considering one point in time. We explain this further in the answer to question 4.*

7. - L185 The route segment description would better fit in the datasets section. *We can remove the route segment descripition in the dataset section if the editor wishs. However, we find it most suitable in this chapter because it is the first time where the term route segment is used and it is needed to understand what is done in the panel data analysis.*
8. - L200 Why location of beginning of segment and not the middle? *The segment id and closest station and stop („Betriebsstelle") at the beginning of the segments was the most accurate and complete information about the localisation of the damage events in the damage database. Due to the heterogeneic shapes and kilometrage of segments, more detailed localisation might have introduced more sources of error and thus abandoned.*
9. - L212 This is a normal logistic regression approach (not random-effects). There seems to be a lot of correlation between the independent variables (rain amount and heavy precipitation event, antecedent precipitation index, 30-day precipitation and soil moisture, topographic index and hazard zone ....). Is that a problem for your analysis? What are the consequences for the interpretation of the results? I assume that the OR for these variables is underestimated because parts of the effect are captured by the correlated variables. *The random variable and random effects model was indeed introduced later in equation 3 a and 3b, the results are shown in table 2 and 3. The logistic regression approach and cross-sectional logit model approach is shown in equation 4, with the results in table 4. The various parameters were all investigated despite carrying information about very similar triggers for damage events to give more insight into the magnitude of the relationship between measurements or indicators and different damage events. A larger problem may be the different scales of the variable units when compared against each other.*
10. - L231 I do not understand the reasoning behind the approach to include annual and seasonal dummies. Please explain it in terms of physical mechanisms. The annual and seasonal variability is already captured by the inclusion of the precipitation events and the precipitation amounts that also have a seasonal cycle and annual variability. What additional processes do the annual and seasonal dummies represent? Please also explain that dummy means binary. Suggestion: If you need to capture an annual cycle a good approach are harmonic functions (e.g. https://doi.org/10.1016/j.spasta.2017.11.007) *The seasonal and annual effects may also lead to characteristics such as varying temperature uncoupled from precipitation, resulting soil infiltration capacity, vitality of the vegetation, foilage coverage, onset of the vegetation period, distribution of storms without especially heavy precipitation etc. that were not captured by the input data. We will also add that the dummy variables are binary.*
11. - L237-238 (Eq 3a and 3b) To me it seems that the method you apply is actually a mixed-effects logistic regression model with random effects (mu_i) and fixed effects (all other effects). I would interpret mu_i as a constant offset that affects the mean probability and depends on the rail segment. Without it the equation has the form of an ordinary logistic regression model. I don't understand the idea behind this approach. What is/are the physical characteristics that differ between segments but are constant within a segment. It seems you already included the relevant geological information as geological control variables (e.g. hazard class, topographic information ...). *After looking further into the definition of models, we agree that due to the fixed-term effects, the model should be considered a mixed model with fixed and random effects. As correctly stated in the comment and described in the article, the component μ_i is individual-specific to the route segment. It was necessary to introduce this variable as during the development and testing of the panel analysis not all*

route segment characteristics could be presented by the hazard class and topographic information. We suspect that the input data resolution is in some cases not sufficient to characterize the route segments in detail, may it be due to the smallscale location of the tracks on a slightly elevated dam, the actual exposition, other mitigating factors such as drainage ditches etc. We are welcome to expand this discussion in the revised version.

12. - L245: Please explain from a physical point of view why you investigate these interactions (and why others are not studied). If you include interaction terms more than one regression coefficient is relevant for the variable. I have doubts that you can use the OR (L219) calculated from just one coefficient to compare the importance of the independent variables if you include interaction terms. *From other studies that have been mentioned in section 2.2.1, rainfall events could be a major trigger for different natural hazards. In the initial exploratory analysis of the relationship between heavy rainfall event represented simply by precipitation the day of and damage events, a limited correlation and a certain time lag could be observed. The additional interaction terms were introduced to account for possible preexisting soil water calculated solely based on the precipitation or also considering evapotransporation.*
13. - Table 1 Why don't you create one table including all variables included in the model for a better overview (soil moisture, seasonal dummy, rail segment, 30-day precipitation, ...). Please also extend the description. What is meant by specified duration? What is the topographic position index? *We are happy to expand the explanations of the variables used in the mixed-effect regression model with random effects:*

	Variable	Description
Dummy variables	0 to 2 days from heavy rainfall event	Binary dummy variable that describes whether the damage event took place between the day of a heavy rainfall event or up to two days after
	- day of heavy rainfall	Binary dummy variable that describes whether the damage event took place on the day of a heavy rainfall event
	- 1 day after heavy rainfall	Binary dummy variable that describes whether the damage event took place one day after a heavy rainfall event
	- 2 days after heavy rainfall	Binary dummy variable that describes whether the damage event took place two days after a heavy rainfall event
Control variables	Precipitation at route segment [mm]	Daily precipitation on the day of the damage event from the 1 km x 1 km HYRAS dataset
	Accumulated precipitation at route segment, 30 days [mm]	30-days antecedent precipitation calculated based on daily precipitation from the 1 km x 1 km HYRAS dataset
	Daily soil moisture at route segment [% nFK]	Daily soil moisture on the day of the damage event from DWD soil moisture 1 km x 1 km grid for agrometeoroligcal applications

.... and in the cross-sectional logit model:

Abbreviation	Description
H	Duration [h] of the heavy rainfall event
RRmean	Mean precipitation [mm] of all RADKLIM pixels within the event zone
SRImean	Mean of the heavy rainfall index (in German “Starkregenindex”) within the event zone: An index describing the speed at which rainfall accumulates within a specified duration of time. Mean of all RADKLIM-pixels within the event zone (Range [0,12])
V3_AVG	Mean of the 21-days antecedent precipitation index within the event zone
ETA	A measure of the extremity of the heavy rain event as a function of the return period as well as

	affected area of an event
VSGL_GRAD	Mean degree of sealing [%]: Percentage of sealed area including road infrastructure within the event zone
STRM_AVG	Mean elevation [m] above sea level within the event zone
TPI_AVG	Mean of the Topographic Position Index that classifies the landscape into upper, middle and lower parts, 2 km circular neighborhood, in the event zone within Germany

Results:

1. - L284 Does this also hold for the individual processes. Fig. 3 only shows the combined result. *These results also hold for the individual processes as mentioned in the Figure caption: „All three natural hazard processes are shown together in the figure as the distribution looks similar for each process when viewed individually.“*
2. - L296 ...the higher the value... (of log likelihood or sample size?) *„The higher the value“ refers to the log likelihood.*
3. - L297 The AIC is useful for comparing models of different complexity. However, you can only compare the AIC if the models are fitted using the same number of observations. This is not the case here. *The AIC shows that the models based on the two different equations (1) and (2) offer a similar quality. Overall the quality of the results is rather low as the number/proportion of events in the panel dataset is small compared to the whole dataset.*
4. - Table 2 and Table 4 Please give the full model equations for the 3 hazards. Do you use the same equation for all 3 hazards (e.g. is the hazard indication map for slope and embankment landslides used for all 3 hazards)? How many parameters did you have to fit for each hazard model? As each segment needs one parameter it must be more than 9679. This is a lot compared to the number of natural hazard events that occurred during the analysis period (14461 trees, 1269 floods, 418 gravitational mass movements). Can you rule out overfitting? *For the panel analysis, the three hazards were fitted/modelled separately to the same equations (1) and (2). For each hazard model, 5 coefficients and one random variable had to be fitted. The small number of observations of damage events is indeed a problem and overfitting cannot be ruled out as the overwhelming majority of observations are without. For the cross-sectional analysis, for each of the three hazards and for each of the investigated variables, a separate model with model coefficients was fitted.,*

1. – L340 indicate … non-linearity … What brings you to this conclusion? *The tables show, at least on the basis of the data and equations applied, that soil moisture has a significant effect on the probability of natural hazards occurring. The analysis shows that a higher soil moisture has a slightly negative effect on the probability in the analysis not broken down by individual days (Table 2). The analysis broken down by days between heavy rainfall and damage events shows a slight positive influence (Table 3). As both results are significant, this could either be a false correlation or an indication of non-linear effects. The latter is also suggested by the graphs in Fig. 4.*
2. - L344 The analysis considers only the interaction terms? Please elaborate what you have done. *The analysis shown in figure 4 uses the equation 3a) with the coefficients calculated for the different natural hazards. For the available range of the control variables, the probabilities predicted/calculated with the three different models is shown.*
3. - Figure 4 What does the figure show? The probability or a prediction of the probability using the statistical model? Panels a,d,e: If precipitation becomes strong enough the day should

automatically become a heavy rainfall event. Why are there two different curves at high precipitation values? Panels c,f,i: Do these curves make any sense in terms of physics? I assume they are a statistical model artifact. Soil moisture was one of the non-significant parameters. *The first part of this comment has been adressed in the answer above. Panels a,d,e: This is correct. With higher precipitation, the curves should be the same, as there would no longer be any days without a heavy rainfall event. The definition of heavy rain events in this analysis is, as described, defined by their Warning Level W3 (events with 25-40 l/m² in 1 hour or 35-60 l/m² in 6 hours). Panels c.f.i: The curves do make sense in terms of physics. In panel c, the probability of a flood is exactly the opposite to the soil infiltration capacity depending on the soil moisture content: water infiltration is low when the soil is especially dry and the pores are closed as well as when they are overfull. In panel f: not significant, but high water infiltration may lead to slope destabilization. In panel i: At very low soil moisture, trees suffer from drought stress and have low vitality. If a heavy rainfall event occurs, the unhealthy trees may be more likely to fall. A similar situation can occur with high soil moisture. The soil is already softened/weak and saturated. In the event of a heavy rainfall event, this can lead to faster falling.*

4. - L384 Could this mean that there are no trees if the soil is sealed and therefore the probability for tree fall is low? *Yes, this can be a possible explanation.*

Technical corrections

1. - L84/85 Is there a difference between events and heavy rainfall events? *There is no difference. For more clarity, we can rewrite the sentence: „In addition, many heavy rainfall events occurred in May and September, while they were rare during winter."*
2. - L177 proximity in space or time? *Proximity in time is meant here.*
3. - L212 is the prime symbol missing from beta2? *Yes, we will add it in the revised version.*
4. - L264 is the prime symbol missing for beta? *Yes, we will add it in the revised version.*