Response to Referees comments:

Natural and human-induced landslides in a tropical mountainous region: the Rift flank west of Lake Kivu (DR Congo)

April 05, 2022

We would like to thank the editor and the three reviewers for their pertinent and constructive comments and also for their appreciation of the quality of the work. We have considered these comments which revealed some weaknesses in the presentation of our work. Through completing the sometimes-divergent suggested edits, the revised manuscript benefits from an improvement in the overall presentation and clarity.

Our answers to the reviewers' comments are presented as follows: the reviewers' comments are shown in **black**; the answers are text in ***blue italics***. And the revised texts are in **green**. The lines of the final manuscript are shown in **purple**, while the lines of the manuscript with the tracked changes are in **orange**.

Contents

I. Reply to Referee # 1

This study explored the impact of forest cover dynamics, roads and mining activities on the occurrence of landslides in the study area. The results showed that susceptibility patterns and area distributions are different between old and recent deep-seated landslides, and natural factors contributing to their occurrence were either different or changed over time, additionally, the forest dynamics and the presence of roads play a key role in their regional distribution pattern. I enjoyed reviewing your paper and believe it contributes to assess landslide susceptibility/risk for the local government. I have made comments in the hopes that they will be useful to improve the manuscript.

The authors thank the reviewer for his/her assessment of the study's contribution to understanding landslide susceptibility/risk at the regional scale.

1.1. General comments:

1.1.1. The abstract should be simplified, and it is the embodiment of the core of the article, so you can delete descriptions that are not very important. In addition, I suggest that research methods of article can be added in the abstract.

We have simplified the abstract while adding info on the methods

L20-22 / 20-22: …To do so, we compile a comprehensive multi-temporal inventory of 2730 landslides of different types and analyze it via frequency-area statistics, frequency ratio distribution and logistic regression susceptibility assessment.

1.1.2. In the introduction, you should be added some contents: (i) background information on the hazards of landslides, (ii) the methods of landside susceptibility, and you can analysis the advantages and disadvantages about different methods, (iii) influence factors of landslide should be listed and analyzed based on the previous achievements, especially in the study area or similar area, (iv) you can simplify some contents, such as lines 60 – 75.

We agree with the comment and included additional relevant information in this section. (i) With regard to the general background information on the hazards of landslides, we believe that the reviewer refers to the temporal aspects of the landslides. We improve the content of the introduction that deals with this issue, specifically with the issues related to human activities. Note that in that respect, **lines 54-66/64-79***, are relevant. (iv)Since this paragraph is also key to support the compilation of the inventory, i.e. one of the key originalities of our research, we avoided simplifying this section too much. (ii) Numerous susceptibility analysis methods have been used in the recent literature, with, as a common goal, the comparison of these methods. This has been extensively described by authors such as Reichenbach et al. (2018) who focus well on showing the advantages and limitations of each. Our study does not aim at evaluating the performance of one method or another but rather to determine the predictors related to the occurrence of the different types of landslides studied. We therefore believe that expanding on this in the introduction is not relevant; especially with the fact susceptibility is only one of the three methods that we use here (with frequency ratio and frequency-area statistics)*

*Nevertheless, we included additional information on landslide susceptibility assessment to further support our methodological choices in the method section (***L223-236** / **246-260***). (iii) The factors of landslide occurrence are described in the methodology and are those used in similar environments but notably in our study area. Nevertheless, the study opted for a selection of variables having a real supposed significance in the occurrence of a particular type of landslide. And it is one of the recommendations of the study to take into account these aspects in the selection of predictive variables supposed to contribute to their occurrence.*

L223-236 / **246-260**: Landslide susceptibility approaches are numerous and more or less complex in terms of modelling implementation and result interpretability (Reichenbach et al., 2018). In a regional analysis where our study area is included, Depicker et al.(2020) used three susceptibility models, namely logistic regression, random forests, and support vector machines. These models gave relatively similar results in terms of quantitative performance and geomorphological plausibility. The same conclusion about marginal differences between susceptibility models can be drawn from many other studies. Since our study does not aim to develop a new methodology nor to show the ability to use complex methods; we relied on a logistic regression approach (Hosmer and Lemeshow, 2000) to determine the predictor variables related to the occurrence of the different types of landslides. Logistic regression isa straightforward method that has been widely used (Reichenbach et al., 2018) and that allows a rather easy interpretation of the results (e.g. Jacobs et al., 2018; Depicker et al., 2020).

Frequency ratio (Lee and Pradhan, 2007) models were used as a complementary approach to better understand the role of each variable in the contribution of the landslide occurrence in terms of process characterization. For example, when slope angle is highlighted by a logistic regression model as a significant variable, we still remain unaware of the types of slopes that actually influence the occurrence of landslides.

1.1.3. In the section 1.1, you can further analyze the relationship between LULC, population and landslides, because the article results showed that the forest dynamics and the presence of roads play a key role in their regional distribution pattern.

The relevance of the remark is well taken in consideration. As explained in "Minor comment 2" the data on population currently available do not allow a regional study at the scale of our study. In addition, we believe that such an analysis, although interesting, would be out of scope here. Nevertheless, we have added information on the roads.

L108-110 / 122-124: … The road network is relatively limited. Most roads are dirt roads and are poorly maintained, and there are no built-up walls (concrete, gabions) to stabilize the cut slopes.

1.1.4. Authors have chosen 10 predictor variables use for the landslide susceptibility by applying different method, however, the triggering factor may be very difference for the shallow landslide and deep-seated landslide, and the assessment result will be changed, have you ever thought about that? If you considered, and you should be list evaluation factor for different landslide type.

This study did not investigate the triggering factors in a direct way. For the shallow landslides, Dewitte al., (2021) demonstrate that all the observed hillslope instabilities during the last 2 decades are associated with rainfall. The research having been carried out in a data-scarce environment where timely access to information on the triggering of landslides is very difficult and where rain gauge information is also very scarce, an analysis of the triggering conditions could only be done over a region that is much larger than our study area using rainfall satellite products with a km-scale spatial resolution (Monsieurs et al., 2019a; 2019b). For a much larger area than our study area, Depicker et al. (2021b) also show the role of triggering rainfall in the spatial distribution of shallow landslides through the use, as rainfall data, of a regional climate model providing a resolution of 2.8 km. Considering what has already been done in other published research work and the context of data-scarcity of our study area, further analysis on the rainfall triggering conditions of the landslides would not have been possible at this stage. .

For the deep-seated landslides, a few of them are associated with rainfall events that are at the origin of landslide clusters. However, such information is only available for a limited number of recent landslides. For the very large majority of the deep-seated landslides, the triggering aspects can only be assumed, going from seismo-tectonic aspects to weathering and climatic controls (Dille et al., 2019; Dewitte et al., 2021). This information is already described in section 1.1.

We made clearer that the purpose of this research is to look at the susceptibility of the landslides, not at their triggering directly. Nevertheless, the difference of predictor variables for both shallow and deep-seated landslides highlighted through the susceptibility analysis allows to discuss triggering conditions (see section 4).

L247-249 / 274-276: The purpose of this research is to examine the predictor variables that contribute to the susceptibility of the different landslide types; not to look directly for their triggering factors. Nevertheless, the different predictors, highlighted by the susceptibility analysis allow to discuss the triggering conditions.

1.1.5. Fig 7a and 7b presented the shallow landslide susceptibility and old deep-seated landslide susceptibility, author have analyzed the reason of differences, however, the results of fig 7a and 7b were also similar in a certain, you should be further explained.

This is a relevant remark for which we added some information.

L447-448 / 501-502: … (Fig. 7). At first sight, both models have spatial similarities of high susceptibility on the eastern part of the region; while the entire western part is weakly susceptible (Fig. 7a,b). However, when we go into detail, the …

1.1.6. The distribution of different landslide was presented in the figure 8, meanwhile, authors should be further analyzed the reason.

Some lines are added for further explanation.

L484-485 / 549: … Both types of landslides are favoured by slopes angles > 20-25°.

L489-492 / 554-557: … probably be explained by a cumulative effect of forest loss, steeper slopes and increased orographic rainfall associated to these elevations (Fig. 8c). The positive frequency ratio in the 1400-1700 m elevation class is related to the area of permanent anthropogenic environment. This zone is characterized by low forest cover and relatively low slopes (Fig. 8c).

1.1.7. In the section 4.3, authors have said rainfall is the trigger of the shallow landslides that we have identified in this study, and the reason explanation was lacked, however, this part have discussed that anthropogenic factors have an obviously effected on landslide, so you need further analyzed the relationship between shallow landslide and rainfall.

In one of the above replies, we explain why the analysis of the rainfall as triggering factor is not possible in our research due to a lack of information (landslide dates, rainfall data) and the limited size of the study area. This is the reason why the triggering analysis could only be performed over a much large region than ours (Monsieurs et al., 1019a, 2019b). Nevertheless, we highlight this issue better in section 2.3.1:

L247-249 / **274-276**: The purpose of this research is to examine the predictor variables that contribute to the susceptibility of the different landslide types; not to look directly for their triggering factors. Nevertheless, the different predictors, highlighted by the susceptibility analysis allow to discuss the triggering conditions.

1.2. Minor comments:

1.2.1. Lines 95-100 or 205: you can draw a figure about the change of LULC in the different years.

This study considers the LULC on the long-term and, as said line ***202*** */* ***224****, completes the study by Depicker et al. (2021b) who analysed the deforestation over the last 20 years and its impacts on landslides. Note that to also reply to the comment "Specific remarks: Table 1" raised by Reviewer #2, we have moved, from the results, the figure (formerly number "Figure 5" and now numbered "Figure 2"on the reconstructed LULC changes. We have also grouped the texts discussing this figure in Section 2.2.*

L208-221 / 231-244 :

In 1955-58, 42 % of the territory was already deforested (Fig. 2a). From 1955-58 to 2016, the loss of forest continued, the forest cover decreasing from 58 % to 24 % of the study area. The area affected by the forest loss over the last 60 years is larger than the remaining permanent forest (Fig. 2b). The comparison of forest areas between 1955-58 and 2016 allows to consider four classes for the forest dynamics. Permanent forest corresponds to forest areas that are present at both dates. The forest loss class corresponds to forests present in 1955-58 that have disappeared in 2016. Since it is impossible to identify for each portion of the landscape the exact cause of forest loss, this class contains a mix of various forest management practices and other causes of forest cut/removal. The forest gain class represents the new forest that has appeared since 1955-58. Similarly, the causes associated with the occurrence of new forest are not exactly known; afforestation and natural forest regeneration being certainly drivers at play. Permanent anthropogenic environment (e.g. cropland, grassland, built-up lands) means that the landscape was not forested in both dates and it is assumed that it remained so during that period.

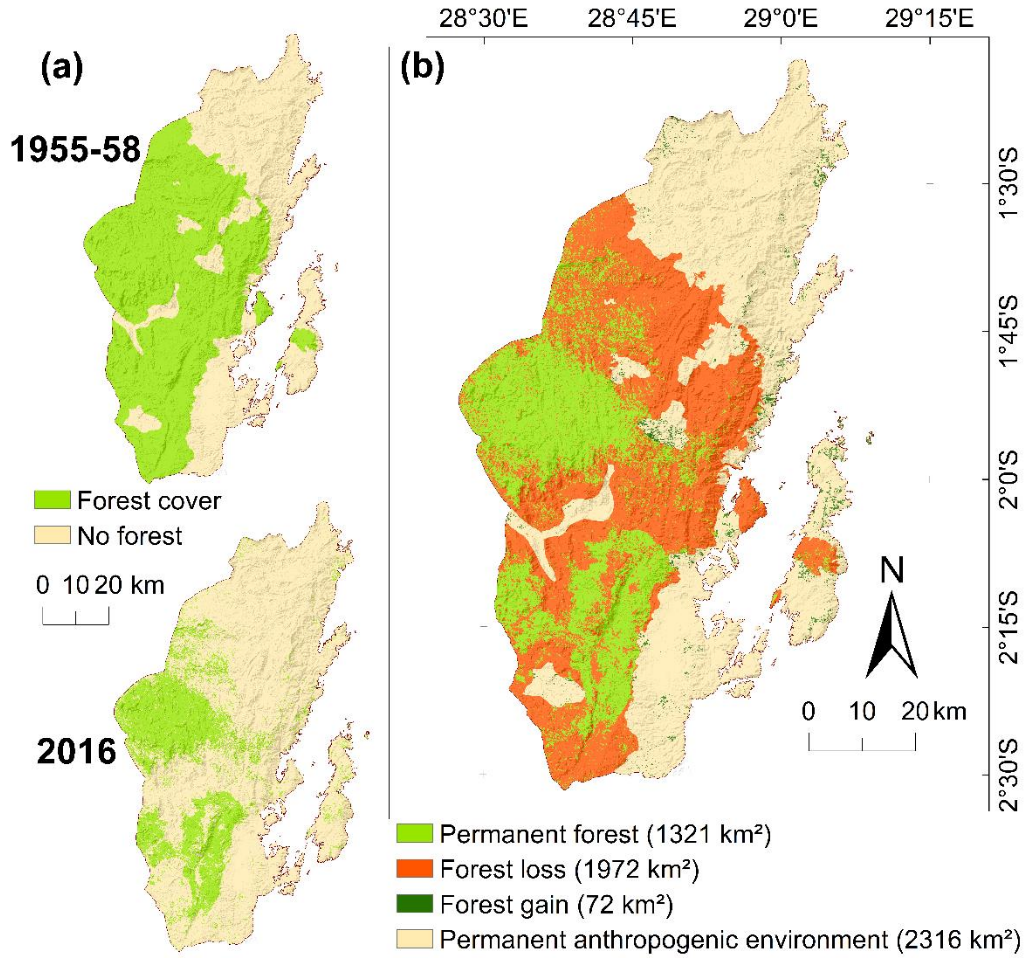
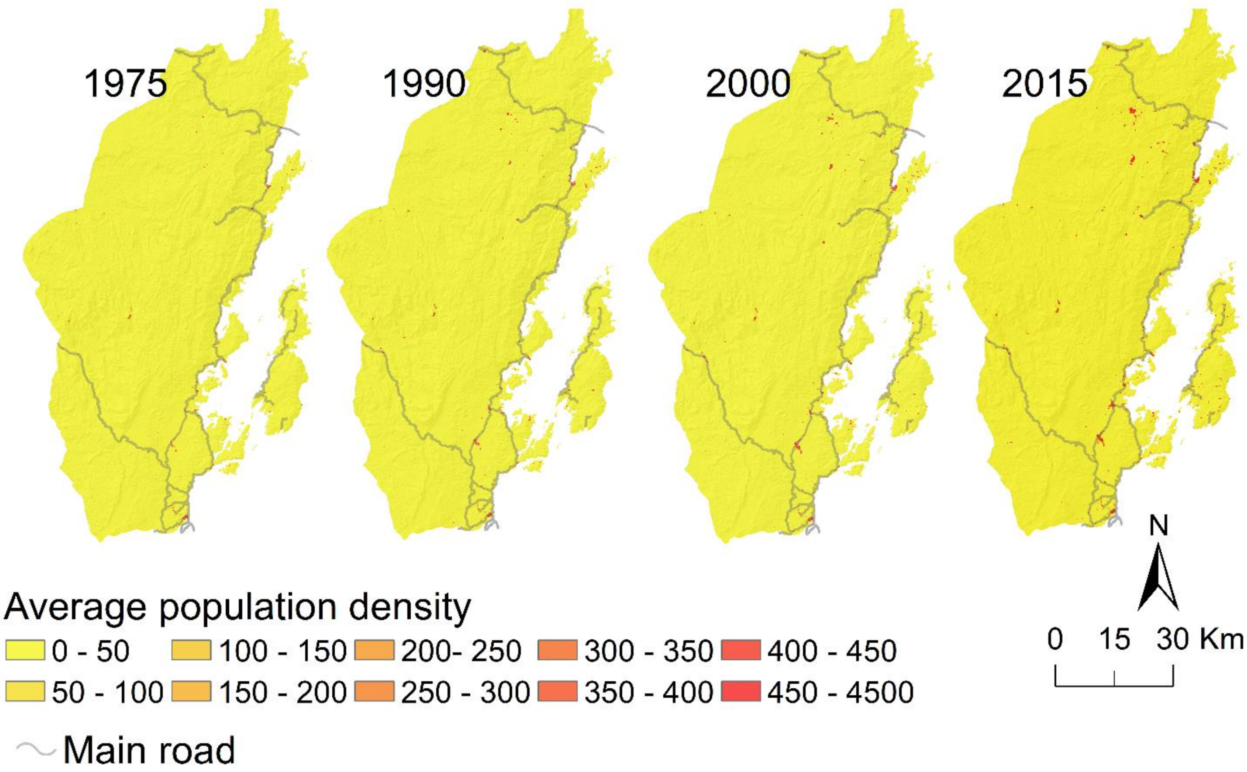


Figure 2: Forest cover dynamics over the last 60 years. (a) Forest cover in 1955-58 and 2016; (b) Areas of forest cover change between 1955-58 and 2016. Details for the images used in this figure are in Table 1.

1.2.2. Line 110: you can draw a figure about population density or the change of population.

There is very little information on the spatial distribution of the population characteristics. For example, the information from the spatially explicit Global Human Settlement Layer46, which is provided for four years: 1975, 1990, 2000 and 2015, is relevant for regional analysis. The data are available at: http://ghsl.jrc.ec.europa.eu/. The gridded data are the result of detecting the built-up land in satellite imagery and subsequently calculating the average population density per built-up pixel (at a 30 m resolution) by means of regional/national census data. However, when looking a specific location like our region, it shows some discrepancies. Adding a figure on the population is not relevant. You can see the figure below.



1.2.3. Lines 155- 160: add the website of different source data.

The text specifies the references or the place to access the sources of the images. In order to make the text shorter, there is no need to specify for example the site to download Google Earth Pro. See lines **143–152** / **163-172.**

1.2.4. Line 175: you can read the relevant references about landslide types, sush as Varnes, 1984; Cruden and Varnes, 1996; Hungr et al., 2014, and it may be better for your research.

We are aware of these relevant references on the types of landslides according to the movement and the materials mobilized; in our research we make reference to Hungr et al. (2014). See line **400** / **444.**

1.2.5. The section 2.2 may be put into section 1.1, you can check it.

Since the reconstruction of the forest cover dynamics is a key element of this study; bringing new results, we believe that it should be included in a separate section of the materials and methods. We have therefore kept the original structured (as also suggested by Reviewer #2).

1.2.6. Lines 300-315: you can simplify.

We made this part clearer. See Lines **320-334** / **357-374**.

Lines 320-323 /**357-361**: Although this is quite a straightforward approach that does not consider the possible interplay among predictor variables, this allows to have a first quantitative insight on the importance…

L334 / **372**: …to indicate for each bin of the predictor variable the probability of occurrence of a landslide.

1.2.7. The format of Table 3 should be nice.

We arranged this table better.

L381 / **423**

Landslide type	Number of LS mapped in the images and checked in the field	TP	FP	FN	Precision (%)	Total number of LS viewed in the field
Deep-seated (old)	248	239	9	60	96	308
Deep-seated (recent)	47	44	3	4	94	51
Shallow	426	420	6	55	99	481
Mining	15	9	6	2	60	17
Road	50	45	5	5	90	55
Total	786	757	29	126	96	912

1.2.8. Lines 530-545: authors have discussed the difference between Van Den Eeckhaut's achievements and this study, and this is well. If you can add others' achievements that is in similar area or nearby the study area, and it may be better.

To our knowledge, there is no other study of this kind in an area similar or nearby to ours. Nevertheless, note that this paragraph has been improved (based also on the comment 1 from Reviewer #3). See lines **527-532** / **587 - 605**.

1.2.9. I suggest that the previous achievements (similar results or research) should be added, and they can abundant your research in the section 4.1-4.4.

As best as we can, we have documented our discussions with relevant studies conducted in the tropical and mountainous context. And the previous work of our research teams has been documented in sections 4.1-4.4 as well.

References

Depicker, A., Jacobs, L., Mboga, N., Smets, B., Van Rompaey, A., Lennert, M., Wolff, E., Kervyn, F., Michellier, C., Dewitte, O. and Govers, G.: Historical dynamics of landslide risk from population and forest-cover changes in the Kivu Rift, Nat. Sustain., 4(11), 965–974, doi:10.1038/s41893-021-00757-9, 2021a.

Depicker, A., Govers, G., Jacobs, L., Campforts, B., Uwihirwe, J. and Dewitte, O.: Interactions between deforestation, landscape rejuvenation, and shallow landslides in the North Tanganyika–Kivu rift region, Africa, Earth Surf. Dyn., 9(3), 445–462, doi:10.5194/esurf-9-445-2021, 2021b.

Dewitte, O., Dille, A., Depicker, A., Kubwimana, D., Maki Mateso, J.-C., Mugaruka Bibentyo, T., Uwihirwe, J. and Monsieurs, E.: Constraining landslide timing in a data-scarce context: from recent to very old processes in the tropical environment of the North Tanganyika-Kivu Rift region, Landslides, 18(1), 161–177, doi:10.1007/s10346-020-01452-0, 2021.

Dille, A., Kervyn, F., Mugaruka Bibentyo, T., Delvaux, D., Ganza, G. B., Ilombe Mawe, G., Kalikone Buzera, C., Safari Nakito, E., Moeyersons, J., Monsieurs, E., Nzolang, C., Smets, B., Kervyn, M. and Dewitte, O.: Causes and triggers of deep-seated hillslope instability in the tropics – Insights from a 60-year record of Ikoma landslide (DR Congo), Geomorphology, 345, 106835, doi:10.1016/j.geomorph.2019.106835, 2019.

Hungr, O., Leroueil, S. and Picarelli, L.: The Varnes classification of landslide types, an update, Landslides, 11(2), 167–194, doi:10.1007/s10346-013-0436-y, 2014.

Monsieurs, Dewitte, Depicker and Demoulin: Towards a Transferable Antecedent Rainfall—Susceptibility Threshold Approach for Landsliding, Water, 11(11), 2202, doi:10.3390/w11112202, 2019a.

Monsieurs, E., Dewitte, O. and Demoulin, A.: A susceptibility-based rainfall threshold approach for landslide occurrence, Nat. Hazards Earth Syst. Sci., 19(4), 775–789, doi:10.5194/nhess-19-775-2019, 2019b.

II. Reply to Referee #2

Dear Authors, I have read and carefully evaluatied your manuscript "Natural and human-induced landslides in a tropical mountainous region: the Rift flank west of Lake Kivu (DR Congo)". I am pleased to report that I found it a relevant, scientifically sound, and well drafted contribution to the journal. It surely deserves publication. However, I have some comments and I recommend to address them to further improve the paper.

Best regards.

The authors sincerely thank the reviewer for his/her evaluation of our manuscript showing its relevance, scientific quality, and writing.

2.1. General comments---

2.1.1. My main concern is about the structure of the paper. Although it is excellently written, I found it too long and with many repetitions. These shortcomings can maybe be fixed with a reorganization of the paper structure. To be more precise, I found that some concepts are repeated at least twice. The first time in the material and methods section: there, they are outlined with a mid-level of detail, and many questions arise to the reader. Then, the results section repeats everything and add some more details answering most of the answers from the readers. This happens e.g. for landslide, forest, and parts of the analysis. Sometimes, things are repeated once more in the discussion. I think this structure does not help the reader and is not effective. You could try to either reorganize the structure (e.g. moving some preliminary results in the methods section) or shortening the information and comments in the material section to the minimum. In any case, please avoid repetitions and be concise and straight to the point.

We understand that the structure of the document can be improved. We did our best to make the reading lighter and avoid repetition. However, we sticked to the "method/result/discussion" structure. Note also that Reviewer #3 specifically acknowledged the relevance of the structure.

Some lines are deleted, for example in:

Introduction section: **L 55-57; 68-71; 142-144; 156-158.**

Materials and methods section: **L 205-206; 216-217; 260-262; 296-306; 360-361.**

Results section: **L 457-458; 472-474; 504-509; 521-522; 534-536.**

Discussions section: **L 563-567; 598-599; 603-605; 619-620.**

We have also grouped the LULC analysis in Section 2.2, moving the now figure 2 from the results to this section. See Lines **L208-221 / 231-244.**

2.1.2. The state of the art review could be improved. Basically, the core of your study is a landslide susceptibility mapping (LSM) activity. Therefore, it would be advisable to include a paragraph about LSM. My advice is not to provide a detailed literature review, but you could focus on works that: (i) pertain to the same/nearby areas or areas with similar characteristics; use the same susceptibility model; try deciphering the important role played by LULC dynamics or urbanization. In the literature, the last point is usually accounted for simply by using land cover maps and/or road network as input variables, but you may briefly acknowledge works that tried alternate approaches or specifically addressed this topic, such as:

Luti, T., Segoni, S., Catani, F., Munafò, M., & Casagli, N. (2020). Integration of remotely sensed soil sealing data in landslide susceptibility mapping. *Remote Sensing*, *12*(9), 1486.

Chen, L., Guo, Z., Yin, K., Shrestha, D. P., & Jin, S. (2019). The influence of land use and land cover change on landslide susceptibility: a case study in Zhushan Town, Xuan'en County (Hubei, China). *Natural hazards and earth system sciences*, *19*(10), 2207-2228.

Shu, H., Hürlimann, M., Molowny-Horas, R., González, M., Pinyol, J., Abancó, C., & Ma, J. (2019). Relation between land cover and landslide susceptibility in Val d'Aran, Pyrenees (Spain): Historical aspects, present situation and forward prediction. *Science of the total environment*, *693*, 133557.

Reichenbach, P., Mondini, A. C., & Rossi, M. (2014). The influence of land use change on landslide susceptibility zonation: the Briga catchment test site (Messina, Italy). *Environmental management*, *54*(6), 1372-1384.

As also suggested by reviewer 1, a paragraph on LSM information has been added in the methodological section 2.3. Furthermore; some of the references suggested here have now been added to the "modified" section 2.2 dedicated to the forest dynamics. See Lines **199** */* **221 - 222**.

L223-236 / **246-260**: Landslide susceptibility approaches are numerous and more or less complex in terms of modelling implementation and result interpretability (Reichenbach et al., 2018). In a regional analysis where our study area is included, Depicker et al.(2020) used three susceptibility models, namely logistic regression, random forests, and support vector machines. These models gave relatively similar results in terms of quantitative performance and geomorphological plausibility. The same conclusion about marginal differences between susceptibility models can be drawn from many other studies. Since our study does not aim to develop a new methodology nor to show the ability to use complex methods; we relied on a logistic regression approach (Hosmer and Lemeshow, 2000) to determine the predictor variables related to the occurrence of the different types of landslides. Logistic regression isa straightforward method that has been widely used (Reichenbach et al., 2018) and that allows a rather easy interpretation of the results (e.g. Jacobs et al., 2018; Depicker et al., 2020).

Frequency ratio (Lee and Pradhan, 2007) models were used as a complementary approach to better understand the role of each variable in the contribution of the landslide occurrence in terms of process characterization. For example, when slope angle is highlighted by a logistic regression model as a significant variable, we still remain unaware of the types of slopes that actually influence the occurrence of landslides.

2.1.3. To perform the LSM and to assess the variable importance you use logistic regression (LR) and frequency ratio (FR). These methods have a long tradition, but maybe they are a little outdated, as more effective and complex methods are continuously proposed (e.g. in the field of machine learning or deep learning). Don't you think this is a weakness of your work? I suggest defending the research strategy of using LR and FR on the introduction.

We appreciate the relevance of your concern using LR and FR methodologies. In a regional study where our study area is included, Depicker et al (2020) used three susceptibility models (logistic regression, random forest, and support vector machine). These models give relatively similar results in terms of susceptibility assessment (both in terms of quantitative performance and geomorphological significance). The same conclusion about marginal differences between susceptibility models can be drawn from many other studies. Since the aim of our study was not to develop a new methodology or to show our ability to use complex methods; we relied on a LR approach, i.e. a method that has been widely used in different regions of the world (Reichenbach et al., 2018) and that allows a rather easy interpretation of the results.

Regarding the FR, the goal of its use is to better understand the role of each variable in the contribution of the landslide occurrence in terms of process characterization. For example, when slope angle is highlighted by the LR as a significant variable, we still remain unaware of the types of slope that actually influence the occurrence of landslides.

We added this information in the method section 2.3.

L224-230 / **247-253**: In a regional analysis where our study area is included, Depicker et al.(2020) used three susceptibility models, namely logistic regression, random forests, and support vector machines. These models gave relatively similar results in terms of quantitative performance and geomorphological plausibility. The same conclusion about marginal differences between susceptibility models can be drawn from many other studies. Since our study does not aim to develop a new methodology nor to show the ability to use complex methods; we relied on a logistic regression approach (Hosmer and Lemeshow, 2000) to determine the predictor variables related to the occurrence of the different types of landslides.

2.1.4. To my understanding, the shape of the area-frequency curves is quite logical. It is normal to have a rollover: it can be interpreted that below that area, the inventory progressively becomes incomplete because smaller landslides are harder to identify (and map), for several reasons. So, I wouldn't spend so many energies to defend the presence of the rollover in your curves: it is a typical feature, useful to identify the size of the landslides that your model could probably miss.

Thank you for the comment, we have judged to maintain these details as it is part of the originality of this study. Nevertheless, the corresponding paragraph has been modified to make this discussion clearer. See Lines **527-532** / **597 - 605**.

2.1.5. If I understood correctly, you assess the importance of a variable by running the susceptibility model with only that single variable. I am not very convinced about this approach. The possible interplay among variables is lost. Moreover, a single-variable susceptibility assessment seems of little use. At present, one of the reasons why more sophisticated LSM methods are used is that they also have internal modules that assess the variable importance.

That is right; we have run the model for each predictor variable selected for shallow landslides and old deep-seated landslides. The goal was to evaluate the extent to which these predictors can be used to differentiate between landslide and no landslide locations. This step is to help us to better understand the multivariate LR models, although we agree that this is not to be considered without caveats. We added a line to make sure to stress this better in the manuscript.

L451-452 / 509-510: All predictors considered for both types of landslides where thus considered in the multivariate logistic regression models (Depicker et al., 2020).

2.2. Specific remarks

2.2.1. L27 which dynamics? Please, be more specific.

Thanks for the comment, it is about the forest loss. But we removed this line to make the abstract shorter.

2.2.2. L35 which susceptibility models?

As written, these are the susceptibility models calibrated for the shallow landslides and old deep-seated landslides. But we removed this line to make the abstract shorter.

2.2.3. L56-59. It depends also how the human intervention was designed and executed. There is a big difference if you just cut a slope and build a house (or a road), or if the cut is accompanied by some additional works (drainages, concrete walls, …). This should also be highlighted elsewhere in the manuscript when you write about this issue.

In this rural environment, concrete walls are almost non-existent. As for the drainage systems, when present, they are very basic (one or two usually-unmaintained ditches on (both) side(s) of the road. Note also that most of the roads are dirt roads, frequently impacted by rill and gully erosion due to a lack of maintenance. The roads are therefore contributing to an undesigned concentration and rerouting of the runoff. We provide these details in the section 1.1.

L109-110 / 122-124: Most roads are dirt roads and are poorly maintained, and there are no built-up walls (concrete, gabions) to stabilize the cut slopes.

2.2.4. Section 1.1 Besides describing the lithology, a short overview of the geological setting could be a nice addendum to this section.

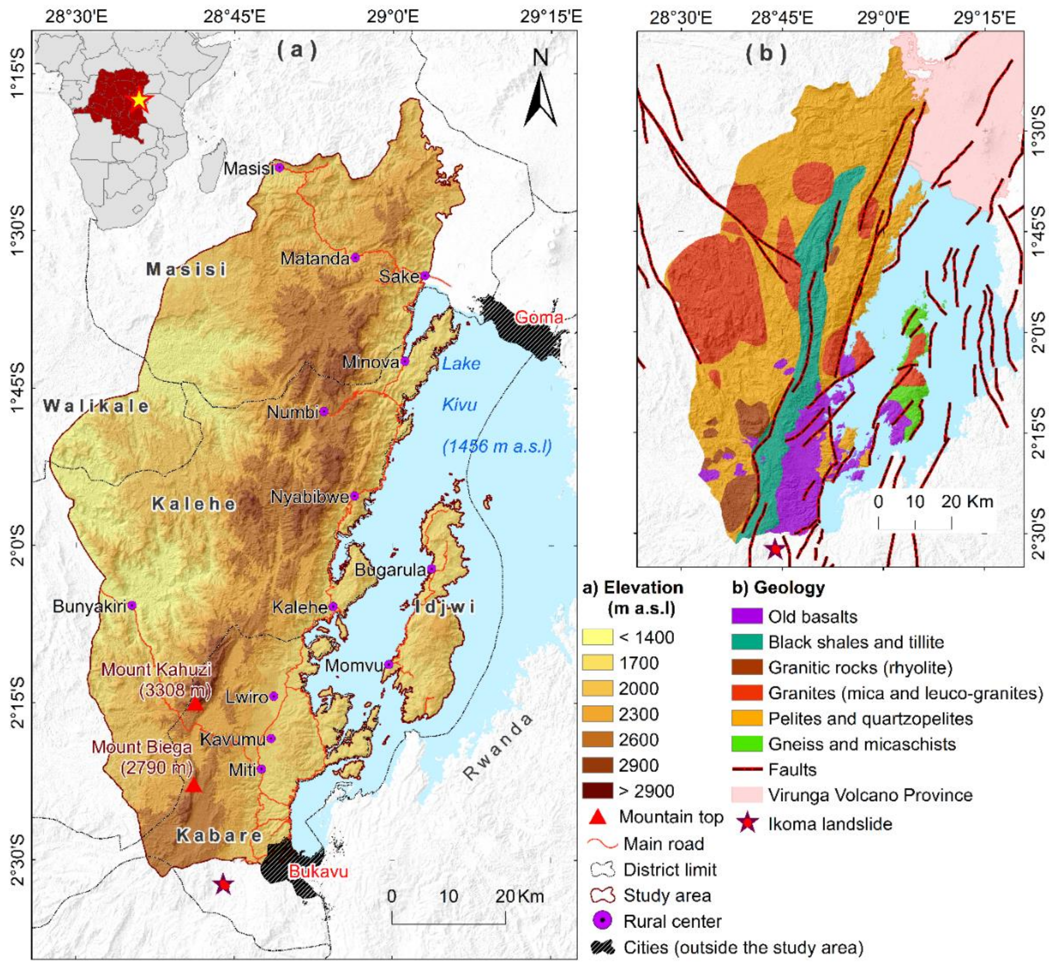
We agree with the relevance of the brief description of the geological setting of the study area.

L80-83 / **94-97:** A significant portion of the study area is made of lithologies from the Archaen, the Mesoproterozoic and the Neoproterozoic, with various degrees of chemical weathering and fracturing. Lastly formed rocks are the old Neogene basalts, highly weathered, that were deposited between 11-4 Ma years.

2.2.5. Fig. 1 For the cities, I suggest using a color that better stands out from the colors used for elevation. E.g. black. And you could also add it in the legend. I initially confused cities outside the study area with parts of the study area.

Thanks for the comment. We adjusted the color for the cities but not for the elevation.

L98 / **112:**



2.2.6. L155-160: From what dates are the images? (This is explained later, but at this point of the manuscript, it is a spontaneous question: see my first general comment).

Thanks for the comment. We indicate here the dates, also in line with your general comment.

L144 / **164**: **…** from 2005 to 2019…

L147-148 / 167-168: …(see Albino et al., (2015) and Dewitte et al., (2021) for technical explanation on the production of the DEM).

2.2.7. L174-178. Usually, a landslide is also considered shallow when the ratio depth/width or depth/length is small. I guess this is also your case?

Our criterion was based on the estimated depth of the surface of rupture. This was assessed through the analysis of the main scarp shape. As we are looking at the conditions that prevailed at the source of the landslides, we did not investigate further their morphometry. Note that in general deep-seated landslides can also have a small depth/length ratio and that, on the other hand, shallow landslides can have a rather long runout (as is frequently observed in our study area).

2.2.8. L225. This is not clear to me.

The SRTM digital terrain model used for the topographic analysis is posterior to the occurrence of the old deep-seated landslides. Therefore, the digital terrain model is affected by the deformation due to the landslides. Calculating the slope values at the level of the main scarp for this type of landslide would give values that are the consequences of landslides rather than the causes of their origin. Hence, we placed a second point outside the landslide on the nearby slope that seems unaffected by landsliding. The morphology of this slope would better reflect the topographic similarity before the triggering of this landslide. We made the text clearer.

L239-242 / 265-268: …In doing so we also avoid the selection of the highest point of the landslide that rarely corresponds to its initiation point (Dille et al., 2019). The digital elevation model used for the analysis (see Table 1) is posterior to the occurrence of the old deep-seated landslides. Therefore, …

L244-245 / 270-272: Calculating the slope values at the level of the landslide head for this type of landslide would give values that are the consequences of landslides rather than the causes of their origin.

2.2.9. Table 1. the meaning of “reference” in the second column is explained only later. This is confusing.

We made it clearer.

L263 / 292:* Each dummy variable is compared with the reference group.

2.2.10. Table 1. The forest dynamics information is very interesting. In my opinion, it deserves also a figure. Unfortunately, the figure comes only after some pages. This is another example of specific issues comprehended in my first general comment.

Thank you for the remark. As replies to the Reviewers #1; we have moved, from result section, the figure on reconstructed LULC changes. We have also grouped the texts discussing this figure in Section 2.2.

L208-221 / 231-244:

In 1955-58, 42 % of the territory was already deforested (Fig. 2a). From 1955-58 to 2016, the loss of forest continued, the forest cover decreasing from 58 % to 24 % of the study area. The area affected by the forest loss over the last 60 years is larger than the remaining permanent forest (Fig. 2b). The comparison of forest areas between 1955-58 and 2016 allows to consider four classes for the forest dynamics. Permanent forest corresponds to forest areas that are present at both dates. The forest loss class corresponds to forests present in 1955-58 that have disappeared in 2016. Since it is impossible to identify for each portion of the landscape the exact cause of forest loss, this class contains a mix of various forest management practices and other causes of forest cut/removal. The forest gain class represents the new forest that has appeared since 1955-58. Similarly, the causes associated with the occurrence of new forest are not exactly known; afforestation and natural forest regeneration being certainly drivers at play. Permanent anthropogenic environment (e.g. cropland, grassland, built-up lands) means that the landscape was not forested in both dates and it is assumed that it remained so during that period.

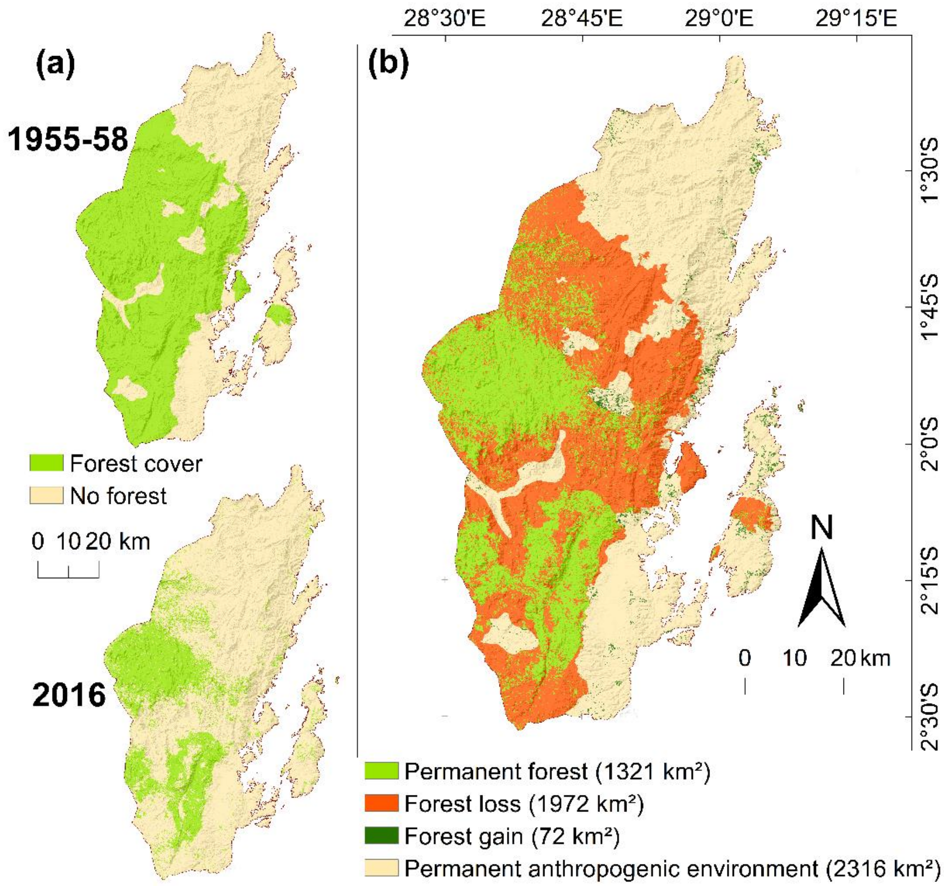
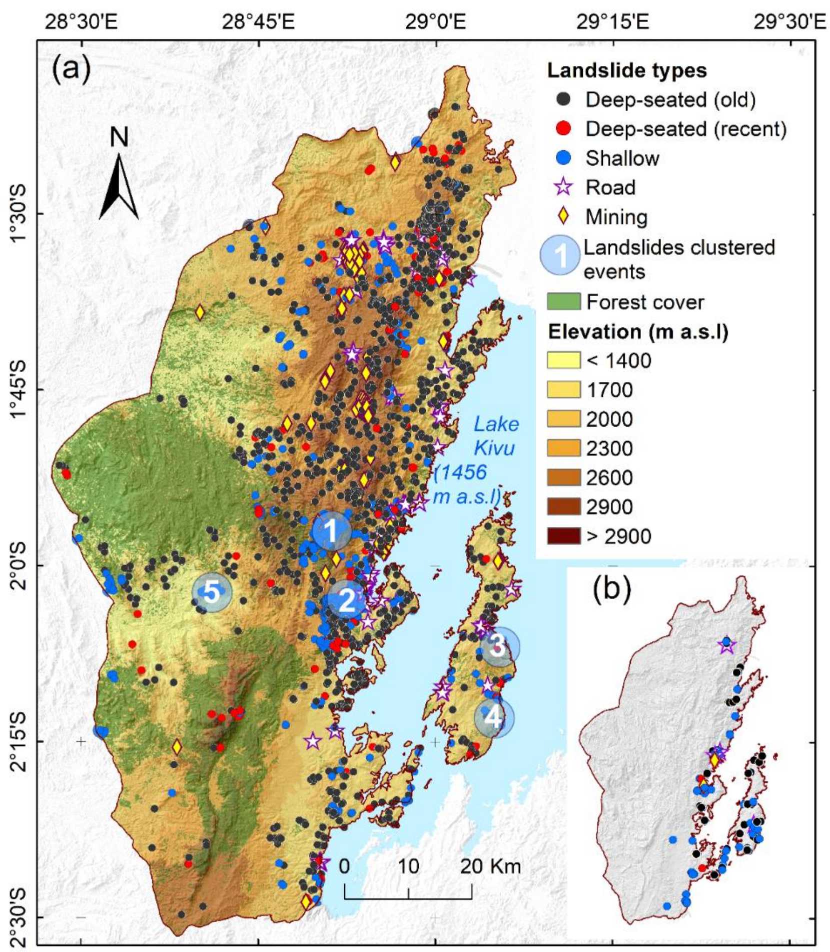


Figure 5: Forest cover dynamics over the last 60 years. (a) Forest cover in 1955-58 and 2016; (b) Areas of forest cover change between 1955-58 and 2016. Details for the images used in this figure are in Table 1.

2.2.11. Figure 2. The forest cover color hides the information about elevation. Didn't you already display the elevation in Fig 1? Here, you could just use hillshade and forest cover.

We tested several ways of presenting this figure, trying colors that contrast better with the elevation and the forest cover. In our opinion, both layers should appear on the figure to show a densification of landslides in the mountainous areas and sparseness in the forest area. Using hillshade alone will not allow readers to locate the topographic context where the different types of landslides are found. We present both types of information as best as possible without hiding the information in the underlying layer.

L 361 / 403:



2.2.12. 377 "these sources"

We corrected the mistake.

L 392 / 435: …these sources…

2.2.13. Table 4. It seems to me that the bedrock lithology has little influence in determining if a landslide will be shallow or deep seated. Maybe because the lithologies produce similar soils and the actual depth of soils (driven by morphology) is the real control?

We indeed show that the lithology is of lesser importance in our study area. For the deep-seated landslides this is in agreement with the findings of Depicker et al. (2021b), which show that the various lithologies in the region have similar rock strength properties. As we also show that the topography and the presence of faults play a role, it is therefore no surprise that the role of lithology is somehow attenuated.

Note also that despite the fact that we use an unprecedented lithological information (in terms of accuracy and resolution), there is a lack of data on the regolith, its depths and the soil types. Field work confirms that soils and regolith can be very different in terms of type and depth, the latter one being highly variable spatially (sometimes over a very short distance of a few meters along a hillslope, one have regolith thickness that varies from > 10 m to nearly zero). The only way to provide an assessment of the regolith thickness at the regional scale is to assume that it varies with slope gradient. It is based on this assumption, that is further supported by the analysis of Depicker et al. (2021b) carried on shallow landslides in the region, that we explain the distribution of the shallow landslides in section 4.3.

2.2.14. 478. I like that recent landslides are reasonably well predicted by a model trained with the old ones. This is like a multitemporal validation. It could be worth mentioning it.

Thank you for your appreciation! We now mention that.

L474-475 / 537-538: …which validates to some extend the multi-temporal predicting performance of the assessment. The…

2.2.15. 493-In an earlier part of the manuscript you mentioned that elevation can be considered a proxy for meteo-climatic characteristics. Why you discard this interpretation here?

You are right. Thanks for the comment. We add a line about this aspect.

L 490-491 / 555: …and increased orographic rainfall associated to these elevations (Fig. 8c).

2.2.16. 593 - Actually, the explanation may be that with this approach you artificially create incompleteness in your inventory. (this interpretation is in accordance with my general comment about frequency-area curves).

In this section our interpretations take into account all 1013 shallow landslides inventoried (see Figure 6), hence there is no creation of incompleteness of the inventory. For some analyses of the frequency density curves excluding event-related landslides from the inventory, we only investigate the potential bias that landslide events could introduce. See Lines **417-429**/**469-483**.

2.2.17. L604 the influence of vegetation on slope stability is somehow a relevant part of the phenomena you are investigating, but this is never mentioned explicitly. Why didn't you openly prepare this issue in advance, and you don't mention it explicitly? Forest loss means (I think) reduced root cohesion and reduced evapotranspiration. I would mention it clearly. You could also make reference to some works such as

Masi, E. B., Segoni, S., & Tofani, V. (2021). Root Reinforcement in Slope Stability Models: A Review. *Geosciences*, *11*(5), 212.

Schwarz, M., Preti, F., Giadrossich, F., Lehmann, P., & Or, D. (2010). Quantifying the role of vegetation in slope stability: A case study in Tuscany (Italy). *Ecological Engineering*, *36*(3), 285-291.

Arnone, E., Caracciolo, D., Noto, L. V., Preti, F., & Bras, R. L. (2016). Modeling the hydrological and mechanical effect of roots on shallow landslides. *Water Resources Research*, *52*(11), 8590-8612.

Glade, T. (2003). Landslide occurrence as a response to land use change: a review of evidence from New Zealand. *Catena*, *51*(3-4), 297-314.

Thank you for the comment, we added two references.

L 598 / 673: … by reduced root cohesion and evapotranspiration due to forest loss(Glade, 2003; Masi et al., 2021), …

2.2.18. 608-612. I think there is (also) another explanation: the slope value you are using is an averaged value, while the built environment may be characterized by a locally steeper value. As instance, in a slope cut you could have a small 90° slope, which may not be well captured by the DTM. Even outside artificial environment, a similar situation may be present.

As mentioned in the methodology, we study the occurrence factors at the scale of a pixel, i.e. a point, taken manually, in the middle of the main scarp for shallow landslides. We have also discarded the shallow landslides found in direct proximity to the roads. Nevertheless, we can indeed not ignore that the SRTM, because of its resolution, does not capture all the slope characteristics such as the cuts. See Lines **237-245** */* **263-273.**

2.2.19. 670-675. The stylistic writing of this part is so different from the rest of the paper. Here the sentences are very short and telegraphic. I suggest to better link them.

Thanks for the comment, we have rewritten this part of work.

L 668-673 / **743-748:** Our analysis shows that the importance of human activities must be considered when investigating landslide occurrence in regions under anthropogenic pressure. This is particularly needed when one sees that the changing spatio-temporal patterns of landslides associated with these activities tend to further exacerbate the risks that the population face. On a more technical/methodological note, our study also demonstrates the importance of considering the timing of landslides in susceptibility and distribution assessments.

References

Depicker, A., Jacobs, L., Delvaux, D., Havenith, H.-B., Maki Mateso, J.-C., Govers, G. and Dewitte, O.: The added value of a regional landslide susceptibility assessment: The western branch of the East African Rift, Geomorphology, 353, 106886, doi:10.1016/j.geomorph.2019.106886, 2020.

Depicker, A., Jacobs, L., Mboga, N., Smets, B., Van Rompaey, A., Lennert, M., Wolff, E., Kervyn, F., Michellier, C., Dewitte, O. and Govers, G.: Historical dynamics of landslide risk from population and forest-cover changes in the Kivu Rift, Nat. Sustain., 4(11), 965–974, doi:10.1038/s41893-021-00757-9, 2021a.

Depicker, A., Govers, G., Jacobs, L., Campforts, B., Uwihirwe, J. and Dewitte, O.: Interactions between deforestation, landscape rejuvenation, and shallow landslides in the North Tanganyika–Kivu rift region, Africa, Earth Surf. Dyn., 9(3), 445–462, doi:10.5194/esurf-9-445-2021, 2021b.

Reichenbach, P., Rossi, M., Malamud, B. D., Mihir, M. and Guzzetti, F.: A review of statistically-based landslide susceptibility models, Earth-Science Rev., 180(March), 60–91, doi:10.1016/j.earscirev.2018.03.001, 2018.

III. Reply to Referee #3

In this works, authors explore the impact of land use change in landslides activity. To this end, they consider the influence of forest cover dynamic (assessed as gains and losses), roads (looking at old and recent roads) and mining activity on landslides occurrence.

The paper is quite complex since, to achieve their main goal, authors had to: (i) compile an exhaustive and accurate landslides inventory; (ii) assess the susceptibility of the area to shallow landslides and to old deep-seated landslides; (iii) assess the influence of geo-topographic and anthropogenic variables (i.e. forest loss, distance to roads and permanent anthropogenic environment) on landslides occurrence.

The paper focuses on an interesting topic, which is undoubtedly highly relevant in the field of landslides assessment. The overall manuscript is well structured, methods are appropriate, results are complete, accurate and reproducible. For all these reasons, in my opinion, it deserves publication on NHESS, with minor revisions.

The authors thank the reviewer for his/her evaluation of the manuscript and for highlighting the scientific relevance of the work.

3.1. General remarks

3.1.1. As the paper is quite complex, it results too long. Therefore I suggest streamlining the content avoiding repetitions. Even if globally it is well written, sentences are quite long and need to be elaborated in a more succinct way.

We thank you for these remarks, and we worked on improving the manuscript by making it shorter and, when possible improving the sentences (keeping in mind that reviewer HH specifically paised the style of the manuscript). In particular, we deleted some lines as answered to the Referee # 2:

For example in:

Introduction section: **L 55-57; 68-71; 142-144; 156-158.**

Materials and methods section: **L 205-206; 216-217; 260-262; 296-306; 360-361.**

Results section: **L 457-458; 472-474; 504-509; 521-522; 534-536.**

Discussions section: **L 563-567; 598-599; 603-605; 619-620.**

We have also grouped the LULC analysis in Section 2.2, moving the now figure 2 from the results to this section. See Lines **L208-221 / 231-244.**

3.1.2. Although the elaboration of a susceptibility maps is not the main objective of this research (indeed the authors applied to this end a classical and intuitive model both for susceptibility – i.e. logistic regression – and for the ranking of the importance of the predictors – i.e. frequency ratio –), other methods existing in literature to this end should be mentioned and cited and your choice for the selected method justified.

Our choices are better explained in the methodological section 2.3 as requested also by Referee #1 and #2.

L223-236 / **246-260**: Landslide susceptibility approaches are numerous and more or less complex in terms of modelling implementation and result interpretability (Reichenbach et al., 2018). In a regional analysis where our study area is included, Depicker et al.(2020) used three susceptibility models, namely logistic regression, random forests, and support vector machines. These models gave relatively similar results in terms of quantitative performance and geomorphological plausibility. The same conclusion about marginal differences between susceptibility models can be drawn from many other studies. Since our study does not aim to develop a new methodology nor to show the ability to use complex methods; we relied on a logistic regression approach (Hosmer and Lemeshow, 2000) to determine the predictor variables related to the occurrence of the different types of landslides. Logistic regression isa straightforward method that has been widely used (Reichenbach et al., 2018) and that allows a rather easy interpretation of the results (e.g. Jacobs et al., 2018; Depicker et al., 2020).

Frequency ratio (Lee and Pradhan, 2007) models were used as a complementary approach to better understand the role of each variable in the contribution of the landslide occurrence in terms of process characterization. For example, when slope angle is highlighted by a logistic regression model as a significant variable, we still remain unaware of the types of slopes that actually influence the occurrence of landslides.

3.2. Specific remarks

3.2.1. Line 225 – The analysis was performed at the scale of one point per landslides, namely the centroid. Other authors use to extract randomly a certain percentage of points per events, or they consider the slope unit, or the highest pixel of each landslides (where the scarp is generally located). Please elaborate more this to justify your choice and its limits.

We do not use the centroid of the entire landslide but a point that is manually placed at the center of the source/trigger area (line 239: we specify "trigger area"). We elaborate more on this point (see answer to Reviewer #2).

L239-242 / 265-286: …In doing so we also avoid the selection of the highest point of the landslide that rarely corresponds to its initiation point (Dille et al., 2019). The digital elevation model used for the analysis (see Table 1) is posterior to the occurrence of the old deep-seated landslides. Therefore, …

L244-245 / 270-272: Calculating the slope values at the level of the landslide head for this type of landslide would give values that are the consequences of landslides rather than the causes of their origin.

3.2.2. Line 252 - OpenStreetMap (OSM) is a digital map database of the world built through crowdsourced volunteered geographic information (VGI). Therefore, there is no systematic quality check performed on the data, and the detail, precision and accuracy varies across space. Can you be sure that no major changes in the network have occurred over the last 60 years or maybe they could have not been detected?

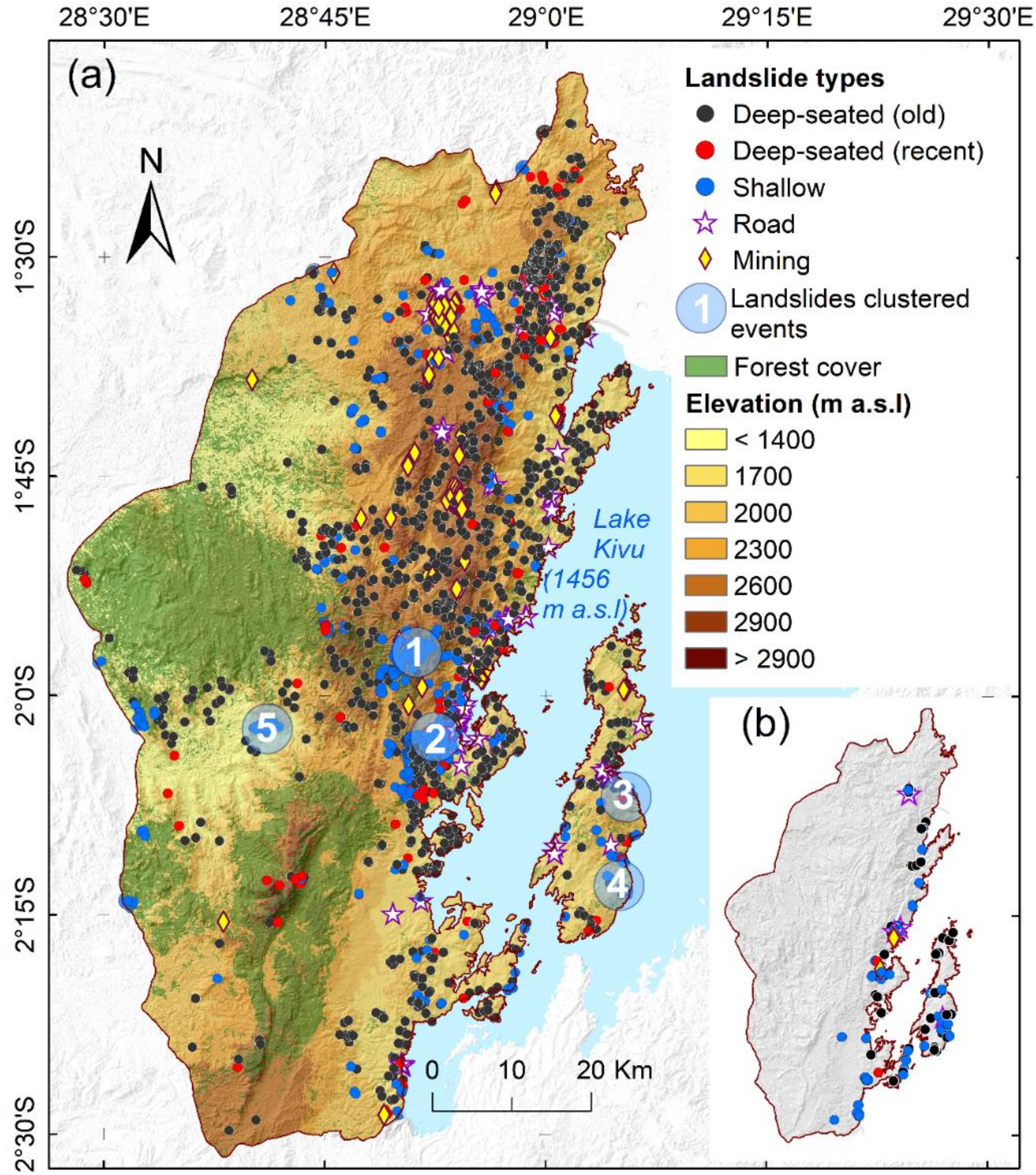
We can confirm that there have been no major changes in the road network. Good knowledge of the study area and the analysis of very high-resolution Google Earth images allowed us to verify the road network proposed by OpenStreetMap.

L 267-268 / 295-296: …Good knowledge of the study area and the analysis of the very high-resolution Google Earth images allowed us to verify the high accuracy of the road network proposed by OpenStreetMap.

3.2.3. Legend of Fig.2: I propose to change “Landslide events” with “Landslides clustered events” or “Shallow landslides clusters”.

Thanks for the comment. We changed it with ‘Landslides clustered events’ as it constituted to both shallow and recent deep-seated landslides.

L 361 / 403:


28°30'E
28°45'E
29°0'E
29°15'E
29°30'E
1°30'S
1°45'S
2°0'S
2°15'S
2°30'S
(a)
N
Landslide types
Deep-seated (old)
Deep-seated (recent)
Shallow
Road
Mining
Landslides clustered events
Forest cover
Elevation (m a.s.l)
< 1400
1700
2000
2300
2600
2900
> 2900
Lake Kivu (1456 m a.s.l)
1
2
3
4
5
0
10
20 Km
(b)