RC2: 'Comment on nhess-2021-336', Anonymous Referee #2, 03 Dec 2021 reply

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.

---GENERAL COMMENTS---

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 could be improved. We will do our best to make the reading lighter and avoid repetition. However, we will probably stick to the "method/result/discussion" structure. Note also that reviewer 3 specifically acknowledge the relevance of the structure.

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.

We agree, as also suggested by reviewer 1, that LSM information could be added in the introduction to better contextualize our research. However, we want to stress that LSM is only one part of our analysis. We appreciate the literature provided. We will see to what extend these studies are relevant to our study area and could be added if they bring an added value. Our research is in a tropical environment. As we pointed out in the manuscript, land uses are very changeable from one season to another and the use of polyculture in the same plot of land is commonplace. Therefore, a "traditional" land use analysis via susceptibility distribution is not possible. We will make sure that this aspect of our research is better highlighted.

As for urbanization, our study concerns a rural environment in Central Africa where major infrastructures are almost absent.

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 will add this information in the method section.

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 will take it into account to lighten the text.

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 will make sure to stress this better in the manuscript.

---SPECIFIC REMARKS---

L27 which dynamics? Please, be more specific.

Thanks for the comment, it is about the forest loss. We will correct this in the text.

L35 which susceptibility models?

As written, these are the susceptibility models calibrated for the shallow landslides and old deep-seated landslides. We will try make the text clearer.

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 will provide these details in the revised version.

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.

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 will adjust it.

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 will indicate here the dates; also in line with your general comment.

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).

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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 will make the text clearer.

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

We will make it clearer.

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.

This figure was placed in the results section as it is the first map of the long-term forest cover dynamics for the region that has been produced hitherto. While Table 1 only serves to present the predictor variables to be used in the study.

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 try to present both types of information as best as possible without hiding the information in the underlying layer.

377 "these sources"

We will correct the mistake. Thank you for the comment.

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.

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 will mention that.

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 will add a few lines about this aspect.

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.

604 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 will take it into consideration.

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. We will mention this to better nuance our interpretation.*

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 will work on this.

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.