Addressing the general comments by reviewer #1

The general concerns about a lack of a susceptibility map were acknowledged and we calculated a susceptibility map and included this in our paper with a new subsection "4.3.1. Susceptibility Map". We calculated the maps for the study site Chrauchtal as an example and show the applicability of the logistic regression models in a predictive setting. As was suggested by the reviewer, we calculated the susceptibility map based on both the *local* model (only including information on this study site) as well as the *cross-regional "all-in-one"* model (containing information from all study sites). To demonstrate the differences, we also included a difference map showing the differences between these two susceptibility maps.

Addressing the specific comments by reviewer #1

L29 When I have read the abstract, I thought that treating shallow landslides as erosional processes could have been a bit of a stretch because the two mechanisms are not the same. This sentence is particularly relevant and I would stress the same concept once more in the conclusion.

We would like to point out, that from a soil science perspective, landslides indeed belong into the category of soil erosion processes. However, we clarified the sentence by:

1. Rearranging the sentence in the abstract to better represent our aim
   L1-3 "Mountainous grassland slopes can be severely affected by soil erosion, among which shallow landslides are a crucial process, indicating instability of slopes. We determine the locations of shallow landslides across different sites to better understand regional differences and to identify their triggering causal factors."
2. Adding a sentence in the conclusion to restate our concept
   L331-332 "We use the term shallow landslides to describe the erosion sites which classifies the erosion feature without implication to the triggering event."

L47 This sentence is not entirely correct, as you are also missing:
Amato, G., Eisank, C., Castro-Camilo, D., & Lombardo, L. (2019). Accounting for covariate distributions in slope-unit-based landslide susceptibility models. A case study in the alpine environment. Engineering geology, 260, 105237. (This one is particularly relevant because it was done in the Alps and proves LASSO to be performing much better than the common Stepwise procedure found in landslide studies).

Lombardo, L., & Tanyas, H. (2021). From scenario-based seismic hazard to scenario-based landslide hazard: fast-forwarding to the future via statistical simulations. Stochastic Environmental Research and Risk Assessment, 1-14.
(This is of minor relevance to the paper although they still use LASSO).

Tanyaş, H., Kirschbaum, D., & Lombardo, L. (2021). Capturing the footprints of ground motion in the spatial distribution of rainfall-induced landslides. Bulletin of Engineering Geology and the Environment, 80(6), 4323-4345.
(This is of minor relevance to the paper although they still use LASSO).

Thank you for pointing this out, we included the missing citations on L48-49.

L82 I know this is not the aim of the paper, but I think it would be very interesting to report the results of the U-Net.
Even just by mentioning the accuracy of this deep learning tool would be a nice addition.

We added the accuracy scores which are presented in Samarin et al. 2020 to this section.
L83-84 "The trained U-Net used in this study has an overall precision of 73%, a recall of 84%, and a F1-score of 78% (Samarin et al., 2020)."
Also, we included one example site (Val Piora) in the supplemental material (S11), to show the complete U-Net mapping results of this site. An example of close up mapping results has been included in the original manuscript and can be seen in Figure 4.

L117 This operation is absolutely correct and yet almost nobody implements it within the landslide community. It ensures that any residual spatial dependence in the data is dissected and therefore removed.
In the landslide literature the only researchers that do it systematically gravitate around Alexander Brenning. I believe, this is very well explained in:

Goetz, J. N., Brenning, A., Petschko, H., & Leopold, P. (2015). Evaluating machine learning and statistical prediction techniques for landslide susceptibility modeling. Computers & geosciences, 81, 1-11.

Steger, S., Brenning, A., Bell, R., Petschko, H., & Glade, T. (2016). Exploring discrepancies between quantitative validation results and the geomorphic plausibility of statistical landslide susceptibility maps. Geomorphology, 262, 8-23.

and I think they deserve to be mentioned here.

Thank you for pointing this out, we included these authors at this point in the text on L120.

L132 Interesting.. I did not know about it.

L148 So, you opted for a balanced presence-absence data. This has some implications in the resulting probability values and their overall distributions which have been nicely explained in:

H. Petschko, A. Brenning, R. Bell, J. Goetz, T. Glade Assessing the quality of landslide susceptibility maps–case study Lower Austria. Nat. Hazards Earth Syst. Sci., 14 (1) (2014), pp. 95-118.

Frattini, P., Crosta, G., & Carrara, A. (2010). Techniques for evaluating the performance of landslide susceptibility models. Engineering geology, 111(1-4), 62-72.

I suggest to mention them in the text.

We included these publications in our text on L152

Fig 4 & 5 A very elegant way to represent the LASSO results!

Thank you.

Fig 6 & 7 As you may have understood by now, I really liked your work. But, if I may suggest something, I would remove Figures 6 and 7 and substitute them with a single figure where the boxplots plotted for Chrauchtal and Val Piora share the same plotting space. You could plot one set in one color, say red and the other in blue and help the reader comparing the effect of each covariate in your model as the test site changes.

As the two figures are right now, it is almost impossible to make a clear comparison and yet it would be an interesting step from a geomorphological perspective.

I do not know how feasible it is but you could even think of plotting the regression coefficients estimated for all test sites, pretty much as you have done for the ROC curves below.

I know it will be messy so, it is just a consideration that I am doing with you. Maybe you could split the figure into subpanels, in one (row?) you can plot the morphometric covariates, in another you can plot the climatic ones, then lithology and then aspect. This could ensure that you have some horizontal space to add the boxplots from the other sites.

Maybe it will still be too messy and difficult to read, so I will leave it up to you.

Thank you for this idea. We improved this figure and increased the readability by combining figures 6 and 7 in to one (now Figure 7), as was suggested above.

L264 That's also very interesting, I would have considered running a all-but-Slope model to see if in a multivariate scheme the slope retains its explanatory power or if it is captured by other morphometric properties. In the end, they all derive from the DEM and part of the spatial information conveyed by the slope may be captured by other covariates.

Thank you for this idea, we included a “no-Slope” model and its performance for all sites in the chapter “4.2. Performance of Slope-only model”.

<u>Addressing the comments by reviewer #2</u>

1) It is not very clear what the authors mean by shallow landslide. In the work of Samarin et al (2020), shallow landslides represent a class of soil erosion (areas with displaced topsoil layers and clear boundaries to the surrounding vegetation). It is possible to insert some pictures of the studied phenomena?

We included multiple images of shallow landslides from different study site regions to elaborate on the meaning of shallow landslides in the context of our study and included a description of the appearance of these sites. (Figure 1 in the Introduction with caption text of Figure 1)

2) The aerial images for the study sites were collected during different years (2013, 2014 and 2015). Which events reference the landslide inventories? Is it possible to include in the text the characteristics of the rainfall events which triggered the shallow landslides?

This is correct, the aerial images, which are the basis for the shallow landslide inventory, are taken at different years (2013, 2014, 2015). This means that depending on the study site, the aerial images was

taken in of of the years 2013, 2014 or 2015. We included the years of the images as information in Table 1 for the individual study sites.
The reason for these different years is that this product by Swisstopo doesn't capture the entire area of Switzerland each year but divides the country up in different sectors, which are covered over multiple years. The selected years in this study are the closest together timewise, that we can get.

The information on the rainfall events are of course matched to the years of the different sites (e.g. for Chrauchtal with the image taken in 2014) the extreme precipitation events of the last 10 and 5 years, respectively, were considered to match the year the aerial image was taken.

We can give information on the extreme precipitation events of the different sites that are available from our data set but we are not able to tell, if this extreme event was really triggering the shallow landslide. We included this information in Table 1 on page 5.

3) The authors have extracted the centre points of shallow landslide with ArcGIS. Nevertheless, I think that the landslide causal factors are better represented by the landslide source areas.

We acknowledge, that for deep seated landslides this may be an important aspect.
However, we argue, that the shallow landslides in our study can be very small (4 sqm) and also often the shapes of these sites are not classic «landslide» shapes with a clear scarp and therefore we chose the center points to better represent the affected areas. Also, Zêzere et al. (2017) showed, that in their study there was little difference between centroid points and rupture zone points. Choosing the centroid point has also been done in other studies (e.g., Wang et al., 2014).
Because we have a high number of shallow landslide points (some valleys up to 8073) we require a high level of automation and it would not be feasible to select the source areas as our points.

If with „landslide source area" the reviewer means having a polygon representing the shallow landslide rather than centroid points, the issue with this is, that we require non-landslide points for the logistic regression approach. For non-landslide sites it is not possible to represent these as polygons and therefore we need points.

4) The authors selected a simplified geological data set containing only the three main rock formation classes (igneous, metamorphic, sedimentary). Generally shallow landslides occur in the soil cover. Why the authors have not considered the pedological map (or the soil cover) of the study sites?

We are sorry, but even though Switzerland is known as the "record keeping country", a pedological map covering the whole country does not (yet) exist for Switzerland and therefore was not available for this study. In fact, this is a great political discussion in Switzerland and just recently new efforts have been started to eventually fill this gap.

<u>List of Changes made to the Manuscript</u>

L1-3 (Abstract) Rearranged these sentences to clarify our topic of research in this paper.

L25 & Figure 1 Included photos of shallow landslides from different study sites to show the typical appearance of this erosion feature and included a description of the affected sites in the caption.

L48-49 Added the citations suggested by Reviewer #1 to the previous citations.

L83-84 Included the accuracy measures of the U-Net mapping tool from our previous study Samarin et al. (2020)

L85 Included reference to supplemental image showing an example site fully mapped with shallow landslides.

Table 1 Included the years when the aerial images were taken, as this information was missing from the study. Furthermore, we included the mean precipitation values (last 10 and 5 years) for the ten study sites taken from the precipitation data set used for modelling the shallow landslide locations.

L120 & L151 Added missing citations as suggested by Reviewer #1.

Figure 7 Here, we merged figures 6 and 7 into one to allow for better comparison between the two figures. Differences and similarities are better understood this way.

L271-273, 277 & Table 4 A no-slope model was calculated for all sites. On these mentioned lines the no-slope model is introduced and the results of this model are included in the table.

L320-328 & Figure 12 We include a new subsection for susceptibility maps, which were calculated for one study site (Chrauchtal) as an example. The maps were calculated using the model results of the locally calculated model as well as the cross-regional all-in-one model (based on all sites simultaneously). The susceptibility maps are another way of demonstrating the quality and applicability of the models.

L330-331 Here, we clarify again, that in our study the term "shallow landslide" does not refer to a specific landslide triggering process, but rather is a term we use to describe the appearance of these bare soil erosion sites.

Smaller changes:

- changed wording of "regional model" to "*local model*" as the name was very close to the other larger-scale model with the name "cross-regional model"
- consistency of spelling: changed the capitalizing of "Slope" in model names and made sure the word starts with a small letter when referring to the actual slope.