McAdoo et al., “Landslides and Development”, Response to Review

This is perhaps the most comprehensive, constructively critical review I (BGM) have received in 25+ years of paper writing. Thank you.

We have attempted to address all of your concerns, even if we respectfully disagree with a minority. We have included both the “track changes” version under the “supplement” based on AR5’s comments, however subsequent minor additions and fixes based on the co-authors’ comments have been wrapped into the final, untracked document (it just got way too messy after the major revisions).

The core concern of this paper is that it makes a link between causation based on a very strong correlation of rainfall-triggered landslides and poorly engineered roads. The literature is surprisingly weak on making this jump, and a geoengineering treatment of this relationship (that is simply accepted in the other papers citied in our study) is beyond the scope of this work. We hope that the findings of this study are convincing enough to justify our novel methodology.

Below we go through AR5’s comments one-by-one, describing the changes made in the manuscript. We firmly believe that this is a much-improved manuscript based on the reviewer’s comments and hope that we have sufficiently addressed each and every one. If there are any questions or concerns, please communicate them to me, writing on behalf of my co-authors.

Sincerely,

Brian G. McAdoo

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AR5: Figure 1

Are these images all the authors’ own?

- “Deeper seated landslides that are accommodates by” typo. Fixed.
- Each figure should be labelled ‘A’, ‘B’, ‘C’, ‘D’ and then the top right figure relabelled I, II, III or something similar. This makes it easier to refer to the figure in text and easier for the reader to quickly distinguish between descriptions. Agreed. Fixed.
- Top left figure. This is an interesting diagram. This should be made into a separate figure and enlarged. It also needs to be clearer what the basis for this figure is in terms of evidence. Give some indication why this is a complete set of possible landslide types near informal roads. Based on the reference (Sidle et al., 2006) and the combined experience of the authors, this is what we have observed in the field. As a relative newcomer to this field (BGM), I was surprised that I could not find a schematic that outlines the modes of failure associated with rural roads. We would all be keen to know if there is a better reference for this. However, as this is not a major focus of the paper, it is helpful for the reader to see what kind of failures are being considered, yet we feel it is better in the context of the examples in Fig. 1.
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AR6: Paragraph starting 'Many villages in the Middle Hills region'. First sentence needs some supporting evidence. I am trying to read into this simple request, however I am challenged to find a way to prove that the villages connected by footpaths (instead of roads?) are indeed connected by footpaths- they just are. And I also think that it is quite logical that footpaths would be more socially and economically limiting than vehicular roads.

AR7: DesInventar. Although DesInventar is a useful source of data, it has methodological biases which are key when interpreting results. I would suggest briefly describing that DesInventar records primarily come from media sources, so may be biased towards particular locations. I would also suggest giving slightly more detail for the in-text citation, e.g., DesInventar Nepal Database. Agreed. However, as is the case in every loss database that we are aware of, data quality is questionable at best, hence the vague language ("scores" of deaths) and no mention of location. To address this concern, we have added a footnote (if this is acceptable to the editors) so as not to complicate the parenthetical citation.

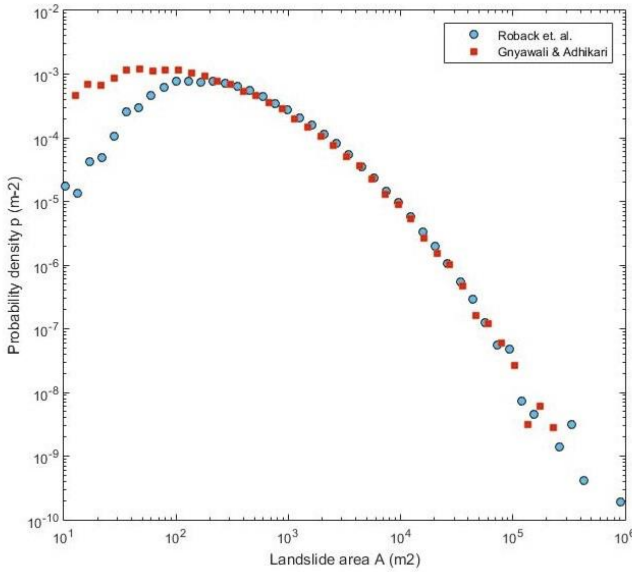
AR8 Method paragraph 1

- Without some indication of timescale and the inventory used, it is not convincing to state that landslides mapped pre the Gorkha earthquake are all triggered by the Monsoon. The region was seismically active before 2015, and there are other drivers of landslides aside from over-steepened roads. I suggest introducing the inventory and then discussing what is implicit about it. It may be useful to draw out additional key points from Petley (2007) rather than simply to direct the reader here. Agreed. I have removed the (confusing, even to us!) interpretation about the roads causing these landslides. However, the overwhelming majority of landslides occur in the Himalaya during the rainy season. This is known, yet we reference Petley et al. (2007) for support. The majority of landslides generated by previous earthquakes would have been long-since covered by vegetation or development in this monsoonal climate.
- State why "Landslides generated by the earthquake…respond more to the geomorphology of the landscape" – the mechanism for this is not clear. Agreed. Reviewing both Roback et al and Gnyawali and Adhikari, I think this statement was incorrect as previously written.

AR9: Methods paragraph 2:

- Not entirely clear what you mean by 'discrete' landslides, and how this differs to the landslides triggered by the earthquake Agreed. Removed "discrete".
- "The landslide inventories we used was created" – typo – were created? Agreed. Fixed, "inventory" to match the verb.
- Generally more needs to be said about this inventory. Creating an inventory of triggered landslides is not a trivial task. How do we know this is substantially complete? This is important for looking at spatial patterns. One option would be to look at the frequency size statistics of landslide areas and compare to already established distributions. Agreed. We have compared our landslide statistics with the Roback paper- While we seem to pick up more smaller landslides, these are not significant in the interpretation of

the results. We have added the figure below to the text, along with a modified beginning of the methods paragraph 2.

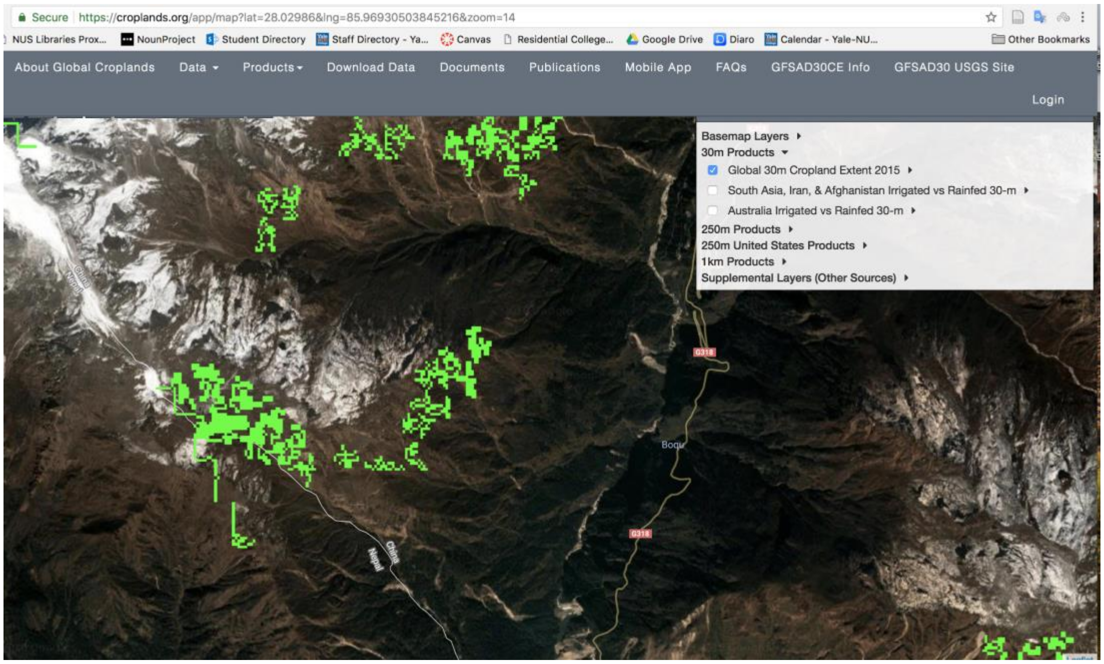


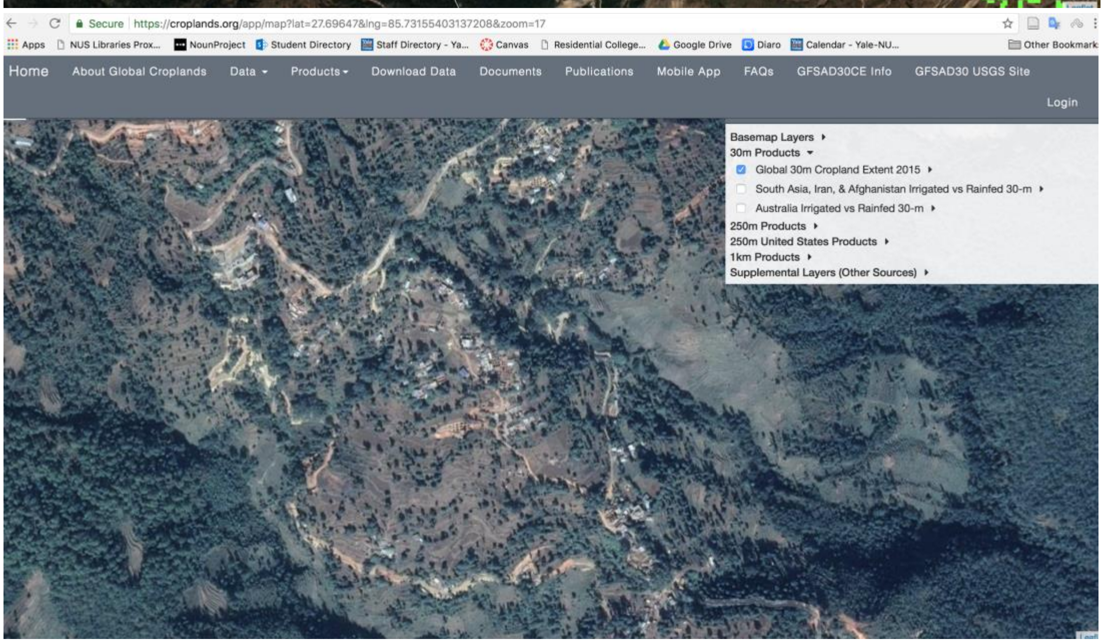
- Be more specific – how many is ‘many landslides’? What percentage is the ‘vast majority’ This is quite difficult as we do not have a count of the ground truthed landslides. Our ground-truthing was based on a rapid visual/spatial identification rather than a comprehensive analysis of each landslide. During field trips up the Arniko Highway/ Bhote Koshi river valley, we had maps and GPS in hand, and were able to visually identify the nearby roadside landslides as well as the larger failures across the valley. I will note that (surprisingly) the other remote sensing papers (Roback et al., Martha, et al.) did not go into detail with the specific mode of landslide failure as these were both based entirely on remotely sensed data. Our paper is also based on satellite data, but we have the advantage of being based in the region and hence these sites are more easily accessed.
- For mapping landslides pre-earthquake, did you use just one image? If so, what is the date of this image? Can you estimate how many of these were relatively fresh (i.e., seasonal) versus older landslides? Multiple images are used to create the landslide inventory. As we are concerned with a binary temporal distribution (pre- vs. post-earthquake) versus a finer grained study of the pre-earthquake landslides, we hope it isn’t necessary at this point to document the specific dates of the imagery that corresponds to the mapped slides- This too is quite difficult in Google Earth as different regions within the area of interest may be covered by different images from the same general time period. An interesting follow up study that uses this methodology might consider mapping all the landslides visible prior to the earthquake over time. However, that is beyond the scope of this study.
- Landslides (particularly smaller ones) tend to be erased from the landscape over time so I am not convinced about using this ‘pre-earthquake’ inventory to look at the spatial distribution of landslides, as this may be incomplete. If it is a case that the pre-earthquake inventory is primarily from one season, this might be more reasonable, but needs to be explained. We have clarified the methods we employed to ensure that we

have, ‘caught’ the smaller, older landslides. As this study is not concerned with the temporal distribution (pre-EQ), it is less critical that we catch all of the older slides.

AR10: Methods paragraph 3:

- The distribution of landslides – state whether you mean spatial, statistical or other type of distribution Area and spatial (geographical). This is clarified in the text.
- State how you compared the distribution of landslides in your inventory to other earthquake triggered inventories. Based on your helpful suggestion, we created a histogram of the landslides in our database to compare it to that in the Roback dataset. While the tail ends match remarkably well, the smaller slides diverge a bit, suggesting we picked up more smaller slides than they have. See new Figure 2.
- It would be useful for this paper to have a specific section or table on data – state what the sources of all the data are that you are using – e.g., soil types, and give more information about the data you have created (the landslide inventory). We agree this would be helpful, but as the sources of data are identified in the references, we are not clear what added benefit a table would add. The post-earthquake landslide database is from Gnyawali and Adhikari, the pre-EQ database is unpublished, but described in this study, and the soils are from Dijkshoorn and Huting. We hope that the additional description of the pre-EQ landslide database is sufficient for the reviewers/editors.
- I see the reasoning that there is more agricultural development in the productive soils, but this needs to be backed up by evidence. There are other data products (e.g., croplands.org) you could use to estimate agricultural or built-up areas to make this statement more robust. Nepal is also rapidly urbanising, which is a different process that may result in road building around small towns and large villages. I believe this should be considered in addition to agricultural areas as an indicator of human impact on the landscape. The evidence for more agricultural development in the productive soils is a simple correlation, and we don’t feel it is too much of a jump to imply causation. Dijkshoorn and Huting point out that these units are agriculturally productive based on the FAO classification, and we see from a GIS overlay that these soils correspond to terracing, villages, roads, etc. In this area of Nepal, the primary industry is farming. As larger villages develop, their primary purpose is to provide services for the surrounding industry (farming). Unfortunately, the croplands.org data for Nepal is wanting- vast areas of rice terraces in the Middle Hills are missing while ‘cropland’ shows up at 4200 m on the very arid Nepal-China border.



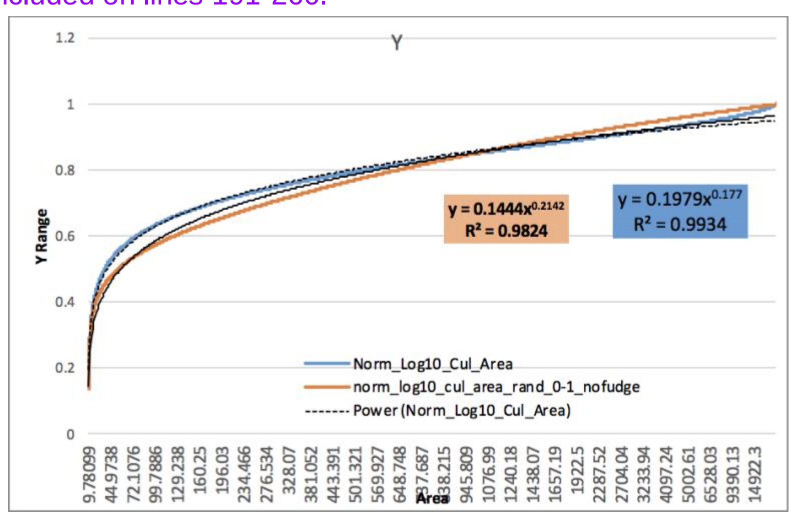


AR11: Methods Paragraph 4:

- Be cautious about stating that the correlation between landslide and road occurrence suggests causality. Agreed. This was misstated. Many papers have made the correlations and have implied causation, but it is very difficult to prove. This paper takes the correlation and brings it one step closer to a stronger link to causation. Please see the amended text.
- I am not convinced about the comparison of landslides in proximity to the road to a random distribution. Landslide location is conditioned by many factors and I do not believe landslides occur randomly across the landscape, even controlling for the location of roads. As a minimum, this needs further explanation and justification in the paper. It

is indeed difficult to determine if the spatial distribution of landslides in these two soil types is random or has some more systematic controls on location. However, when compared to truly randomised location data, we were surprised to find that they matched so well. We too would have expected more separation. This comment does point out that we needed to more clearly state our hypothesis, which we have sought to do in the clarifying paragraph on lines 180 to 189.

- State the method used to measure whether observed landslides match the randomly generated ones. This is not clear, as the location of randomly generated landslides will be different on each Monte Carlo iteration. State what part of the landslide you measure (centroid? Crown? Toe?) in relation to what (distance to nearest road, count within a buffer of a road?). The paragraph on lines 191 to 208 describe the methodology in more detail- we first generated the 10 sets of random areas that all fall within the distribution of the measure slides, then we randomly distributed those slides across the two soil units in the district. We seek to clarify the question about which part of the landslide is measured by stating that 'any part' of the landslide that touches the buffer, 'counts'.
- Sentence starting 'the pre-earthquake landslides have a normal distribution' – distribution of what? Size, distance? I would like to invent a word, "areal" which is the adjective form of 'area'. We have tried to clarify in the rewriting of the paragraph.
- State the resolution of the Google Earth imagery (which is typically sub-metre). I would be surprised if you are missing all but a small portion of the smallest earthquake triggered landslides due to issues of resolution, and believe this may be a result of removal of smaller landslides from the landscape by erosion, revegetation, ploughing etc. As shown in the histogram, we were able to resolve many more smaller landslides than previous studies.
- State how you have performed the curve-fitting of these distributions and tested the goodness of fit. We plotted the normalised, log cumulative areas from the real data, fit a curve, generated a series of random numbers and plugged them back into the equation. We then used an R^2 value greater than 0.98 to determine the goodness of fit of the modeled normalised log cumulative data with the measured areas. A simplified version of this is included on lines 191-200.



- Why only 10 runs of the Monte Carlo simulation? See e.g., http://kb.palisade.com/index.php?pg=kb.page&id=125 for a discussion of number of iterations versus confidence intervals. **Agreed-** 10 is too few for a true Monte Carlo. We have changed the text by removing the term, "Monte Carlo" which highlights that there are only 10 runs. If our math based on the above link is correct, to get a 95% confidence with a 500 m margin of error, we would be better off doing on the order of 500 runs. However, as there are 10 randomised sets of areas over each dataset, and both were run 10 times, it really represents the stochasticity of 100 runs, which is closer to the 500. (The member of our team that ran the simulations (MQ) is on maternity leave, and out of contact, unfortunately.)

AR12: Results paragraph 1:

- You did not mention the fieldwork in the methods section, it seems slightly odd to start the results by discussing field observations. This was meant to be a generic 'field observations' to set up the advantage of doing satellite-based studies. We have clarified this to make it less-specific, not referring to this particular study.
- The second (long) sentence of this paragraph needs splitting and expanding upon. It was not clear from the methods that you focus the analysis on agricultural areas and why this is done. Agreed. We broke up the paragraph into more distinct sentences. However, on lines 216-218, we do state the focus on agricultural soil types, however we again attempted to clarify in the rewritten sentences.
- What is a 'genetic' relationship? "Relating to origin, or arising from a common origin"- dictionary.com.

AR13: Results paragraph 2:

- Why state a range (20-25%) for earthquake triggered landslides occurring within 100m of a road, but no range for pre-earthquake triggered landslides? Be specific rather than stating 'nearly 50%'. Agreed. We have fixed to be more specific.
- Not clear why you are discussing the total area of landslides, particularly when the sample size is two orders of magnitude different between the monsoon and earthquake triggered landslides. Agreed. We have deleted this detail, as it is not particularly pertinent to the argument.
- As stated previously, I believe the difference in average area may be due to the difference between analysing a triggered versus multi-temporal landslide inventory. For distributions that span multiple orders of magnitude and are skewed, it may be more appropriate to analyse the mode or median landslide area. The median is also higher for the rainfall triggered slides, as is the mode (there are no modal values for the pre-landslide dataset, so we rounded the data to the nearest 10, which returned a mode of 620 m^2 for the rainfall slides and 40 m^2 for the earthquake slides). We did add the mean and median values on an enlarged histogram in Fig, 4.

AR14: Figure 3

- Add legend indicating difference between bars and lines. Done
- Add description of sub-figure in the figure caption. Done

- Ensure axes are appropriately labelled in sub-figure. Unclear what has been normalised and why. Done

AR15: Results paragraph 3

- This paragraph is very conversational in style and needs tightening up, e.g., what is a 'kink in the trend'. Why 'borrow from the fractal literature'? Agreed. We have tried to formalise the language.
- This discussion about a 'crossover length' is unclear – explain in the text why one would expect to see a decline in number of landslides at a given distance from the road. The key here is the added, "mechanical influence", or how far away from the road cut are the mechanical effects, "felt". It is beyond the scope of this paper to give this a proper mechanical treatment, however we would hope that this might inspire future researchers to do a more detailed study in a smaller area.
- Generally, the concepts in this paragraph are interesting but need further explanation and possible supporting evidence. Hopefully the above .

AR16: Results paragraph 4. Give evidence to support the statement that the roads follow river valleys and ravines. This was based on the comments of a previous reviewer. A visual inspection of the landscape, and our collective field experience, bears this out. Certainly, there are also mid-slope roads, but this is really moot as explained later in the paragraph. It would have indeed been helpful to do a similar buffer analysis to quantify this distances roads are from ridgelines and river valleys, however that is beyond the scope of this paper.

AR17: Discussion paragraph 1

- In the methods, state how you systematically separated out informal and formal roads from the OSM dataset. This is, as we think you must know, a bit messy. Like many crowdsourced databases, the OSM data can be inconsistent based on the user that input the data. The OSM data comes with over 20 different road classes, so depending on how the mapper classifies a road (and what that classification is based on), there can be a lot of variation. To counter this, we overlaid the OSM data with the satellite data in a GIS, and made visual assessments as to the quality of the mapped paths/roads. As our Nepali colleagues are quite familiar with some of these areas (but certainly not all!), they were able to let us know that, "Yes, this path labeled in one area as a 'path' can handle a motorbike or jeep, whereas another "path" is only foot traffic." This is where we rely on local knowledge- it isn't perfect, but it is better than nothing.
- In the results section, I suggest presenting a brief quantitative analysis of kilometres of road length per soil type to support the statement 'with its good agricultural soils and vast network of informal roads'). While we appreciate the need for quantification, the map in Figure 2 clearly shows the overwhelming concentration of roads in the more productive CMu soils.
- As per comment AR10, in addition to agriculture, urbanisation is another form of development. At present, you imply that good soil is the only control over which areas are developing (and where there are more roads). I believe the language needs adjusting (or analysis also performed on small towns and large villages) to reflect that

soil quality is not the only indicator of development. The concept of “urban” is a bit lost in this context. Yes, there are areas with higher population density but to call a collection of 20-30 houses on the side of a valley, “urban” just seems odd. We were somewhat surprised to see the visual correlation between landslides and soil type, especially when the other studies (Roback et al., Gnyawali and Adhikari, and Martha et al.) ignore soil type and focus on bedrock despite the shallow nature of most of the slides. Because this is a new window of analysis in this region, with this event, we choose to stay focused on soil type, and perhaps leave more detailed comparison with urban development for another study.

AR18: Discussion paragraph 2. If something ‘is well known’, then add citations to support it. More broadly, there are very few references in the discussion to frame your results in terms of previous work done on this topic. Agreed. “Well known” was removed and a citation added.

AR19: Discussion paragraph 3. As per AR9 and AR11, the size (or area) of landslides is an area where a lot of work has been done (e.g., Stark and Hovius, 2001; Malamud *et al.*, 2004; Stark and Guzzetti, 2009 amongst others). I believe it is possible that your findings in terms of landslide size may be a result of sampling rather than process necessarily. I am not sure what findings in terms of landslide size AR is referring to here. While I am certain that AR is correct, the comments in this paragraph are based on the data- “the average size (of the pre-earthquake landslides) is larger”. Because both the pre- and post-EQ data were collected using Google Earth imagery with the same resolution, it is less likely that the differences could have resulted from sampling from datasets with different resolutions causing us to skew the data in one direction or the other.

AR20: Discussion paragraph 4

- This is a little confusing to introduce the Maoist insurgency here without any prior discussion of the insurgency or its implications for road building. Agreed. Perhaps we are trying to over-interpret the data. We have removed this section to be considered in an expanded paper.
- Generally in this paragraph, the discussion about correlation between deaths from landslides and increase in road length sounds more like results than discussion, and would benefit from evidencing.
- I am concerned about the use of DesInventar here to imply an indirect link between political regime and deaths from landslides. As mentioned previously, much of the data for DesInventar comes from media reports, and thus has biases. The links between politics and journalism are of course too complex to discuss in detail in this paper, but there needs to be some acknowledgement from earlier on in the paper that DesInventar has biases and this uncertainty acknowledged when discussing DesInventar. I suggest that Aryal (2012) should be read and possibly cited to give some context.

AR21: Figure 4

- Give legend entries titles. Figure 4 removed
- In legend, state deaths from landslides (otherwise it implies total deaths from all causes)

AR22: Conclusions

- Without further discussion in previous parts of the paper, I am not convinced that you are comparing datasets of human versus natural triggered landslides. This is the hard question- perhaps impossible. How can we attribute any given landslide to any particular cause? These data show that the roads are having a significant impact on the social and physical landscape.
- Some of the conclusions are introducing new ideas and read more like a discussion. We assume that AR is referring to the call for Green roads. Based on the results and discussion therein, we chose to put next steps in the conclusion. Furthermore, a paper like this has policy implications and one of us (KSR) is working for UN Environment to ensure that work like this gets to the policymakers that are in a place to invest in more sustainable solutions. This also helps explain the less formal tone we are trying to affect.

7091-Roads and landslides in Nepal: How development affects environmental risk

McAdoo , B.G. (1)., Quak, M. (1), Gnyawali, K. R. (2), Adhikari, B. R. (3), Devkota, S. (3), Rajbhandari, P. (4), Sudmeier-Rieux, K. (5)

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Abstract. The number of deaths from landslides in Nepal has been increasing dramatically due to a complex combination of earthquakes, climate change, and an explosion of road construction that will only be increasing as China's Belt and Road Initiative seeks to construct three major trunk roads through the Nepali Himalaya. To determine the effect of informal roads on generating landslides, we measure the distance between roads and landslides triggered by the 2015 Gorkha earthquake and monsoon rainfalls prior to 2015, as well as a set of randomly located landslides. As landslides generated by earthquakes are generally related to the geology, geomorphology and earthquake parameters, their distribution should be distinct from the rainfall-triggered slides that are more impacted by land use. We find that monsoon-generated landslides are almost twice as likely to occur within 100 m of a road than the landslides generated by the earthquake and the distribution of random slides in the same area. Based on these findings, geoscientists, planners and policymakers must consider how roads are altering the landscape, and how development affects the physical (and ecological), socio-political and economic factors that increases risk in exposed communities.

1. Introduction

On 29 and 30 July 2015, during the first monsoon season after the Mw=7.8 Gorkha earthquake, a dramatic cloudburst triggered landslides that killed 29 people in Nepal's Western Region (**BBC, 2015**). These deadly landslides and many others like them are not solely the result of intensified rainfall associated with climate change (**Bharti et al., 2016)**, but a complex intersection of socio-economic factors with a highly-altered physical landscape where informal, non-engineered roads regularly fail during the annual monsoon season (**Petley et al., 2007**). This problem will become more acute as China's Belt and Road Initiative (BRI) aims to expand trade into Nepal, India and beyond via a series of trans-Himalayan corridors which traverse some of the world's most geomorphically-complex terrain (**Bhushal, 2017**). This expanded transportation network will have unintended effects on the surrounding landscapes as villages seek to link to these lines with roads constructed and maintained with severely limited resources, putting them more at risk of landsliding.

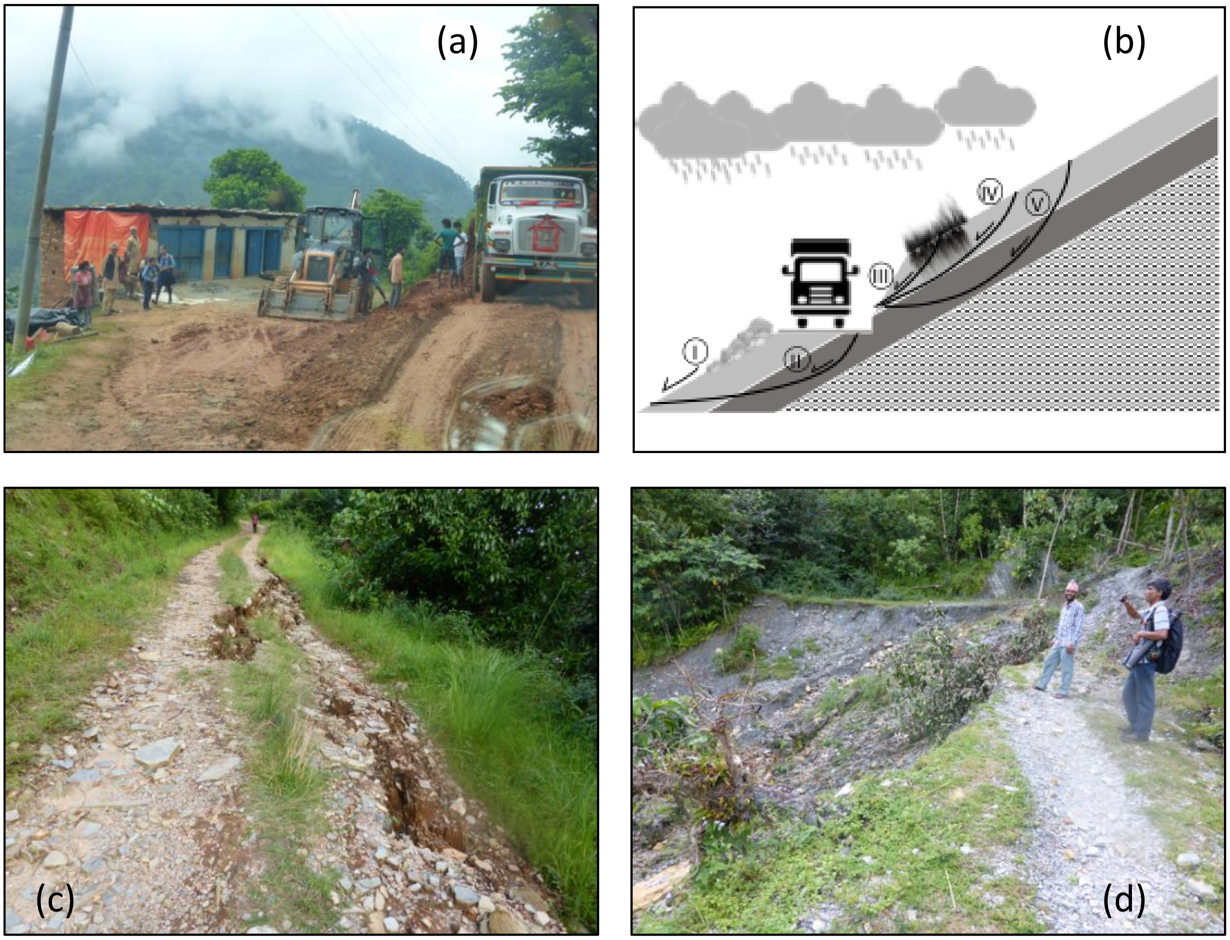

Figure 1. Informal, rural roads in Sindhupalchok District, Nepal. **(a)** Earth-moving equipment is hired by villagers to expand footpaths into roads that bring goods and services to isolated locations. **(b)** We see 5 primary modes of potentially damaging mass movements caused by informal road construction- a) debris flows from excavated material stored on the downslope side of the road; b) Deeper seated landslides that are accommodated by poor road drainage; c) Shallow failures close to the road caused by oversteepened road cuts that can be mitigated by planting; d) Shallow landslides caused by oversteepening that include potentially stabilising roots from vegetation; e) Deeper seated failures below root zone related to road cuts. **(c)** and **(d)** Without proper engineering (slope gradients, drainage, etc.), landslides are triggered on these rural roads during heavy monsoonal rains, damaging land, structures, and roads, and endangering human lives and livelihoods. *Images by the authors.*

Many villages in the Middle Hills region of rural Nepal are connected by simple footpaths that limit social and economic opportunity. As the nation continues developing, communities hire heavy machinery (funded in part by remittances sent from overseas) to expand these pathways into vehicular roads for better access to markets, educational opportunities, and healthcare . The resulting informal roads often create landslides by undercutting slopes, providing pathways for water to seep into potential slide planes, and producing debris that is easily mobilised during heavy rainfall (e.g. **Sidle et al., 2006**; **Fig. 1**). Landslides disrupt the transportation networks that bring much needed goods and services to and from rural communities, damage agricultural lands in regions where subsistence farming is the norm, and cause scores of deaths every year (**DesInventar**[1]**, Nepal Profile, 2016**), all counteracting the sought-after developmental gains.

To better understand the link between the development that will follow the BRI-related development and geomorphic risk, we examine the relationship between roads and landslides in the Sindhupalchok district of Central Nepal (**Fig. 3**). The 2015 Gorkha earthquake heavily impacted Sindhupalchok, where over 95% of the houses were severely damaged and over a third of the deaths occurred here (**ReliefWeb, 2017**). The earthquake also generated thousands of co-seismic landslides in this district (**Gnyawali and Adhikari, 2017; Fig. 3a**), many of which intersect rural roads. By comparing the spatial distribution of slope failures generated before and during the Gorkha earthquake with a randomly-distributed suite of landslides, we present compelling evidence that landslides associated with informal roads are a significant and often overlooked geomorphic agent and compromise the development trajectory in villages that sought to gain from the road construction. Based on these results, we show that this mode of failure should be carefully considered in studies of landslide distribution and development planning, especially as the BRI extends the road network through the Himalaya.

2. Methods

To help determine the significance of roads in the generation of landslides, we compare the landslides present before the Gorkha earthquake with those triggered by the earthquake itself. Implicit in this comparison is that the majority of landslides present before the earthquake were generated by monsoonal rains- **Petley et al. (2007**) show that 90% of fatal landslides occur during the rainy season (landslides that occur without fatalities likely go unreported, therefore it is possible that there are non-fatal landslides that occur throughout the year). Landslides generated by the earthquake, however, respond less to the human-altered features, and more to the geomorphology of the landscape more than the human-altered features, degree of weathering of the bedrock, and proximity to the earthquake rupture zone (**Gnyawali and Adhikari, 2017; Roback et al., 2018**). If there is a strong spatial correlation between the roads and either set of landslides, we can begin to better understand how important these roads are in altering both the physical and social landscapes.

There were on the order of 20,000 landslides generated by the Gorkha earthquake (**Gnyawali and Adhikari, 2017; Roback et al., 2018**), of which we analysed 8,238 in Sindhupalchok district and 139 slides present before the earthquake. The landslide inventory we used was created by manually digitizing the bare earth-landslide scars in Google Earth from high resolution satellite images (sub-metre), at an eye altitude of 500 meters, correspondingly minimum detected landslide area being around 20 square meters (**Gnyawali and Adhikari, 2017**). The post-earthquake landslide inventory consist of scars observed in the image between April 25 (main -shock day) to May 25, 2015, during the dry season before the monsoon rains in June. Similarly, the pre-earthquake landslide inventory consists of failures identified in the area before the earthquakeSlides that were present in images between October 2014 and February

[1] The mortality statistics in the DesInventar database are likely a minimum, as much of their data comes from media reports that originate in more accessible areas.

2015 were mapped- these include slides generated during the 2014 monsoon season as well as older slides. We ground truthed many of the slides visible from the Arniko Highway- The vast majority of slides we observed involve the regolith with very few deep-seated failures that involve the bedrock.

The area and spatial distribution of the Gorkha earthquake-generated landslides used in this study (**Gnyawali and Adhikari, 2017)** is similar to other catalogues of the same event (**Roback et al., 2018; Martha et al., 2016; Fig. 2**) where the primary controls are related to proximity to earthquake rupture zone and peak ground acceleration, as well as the physical characteristics of the topography including aspect, slope, curvature and bedrock geology **(Fig. 3**). The majority of landslides (7,230 or 86%) occur in two soil types- the better developed, agricultural humic cambisols (CMu), and the less-productive eutric regosols (RGe) that occur in higher, more arid zones (**Dijkshoorn and Huting, 2009**; **Fig. 3a**). Of the 7,091 earthquake-triggered landslides, 2,687, or 38% are in the RGe soil type, whereas only 35 of 139 (25%) pre-earthquake landslides occur in this soil type. The remaining 104 monsoon-triggered landslides in the CMu are in the area with more agricultural development, and hence more exposed communities and roads.

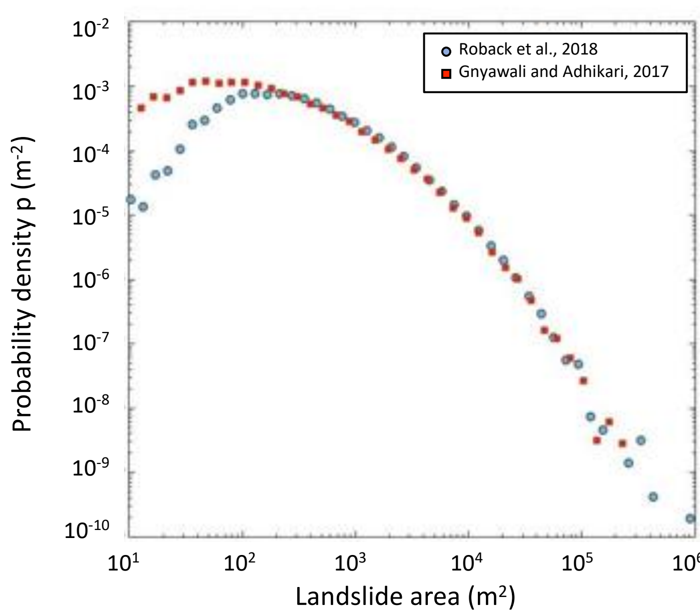

Figure 2. Probability density-area statistics of the Gorkha earthquake triggered landslide inventory used in this study compared to the inventory generated by Roback et al., 2018. The two curves diverge at slides with areas less than around 200 m^2 suggesting that the Gnyawali and Adhikari (2017) data selected more smaller slides.

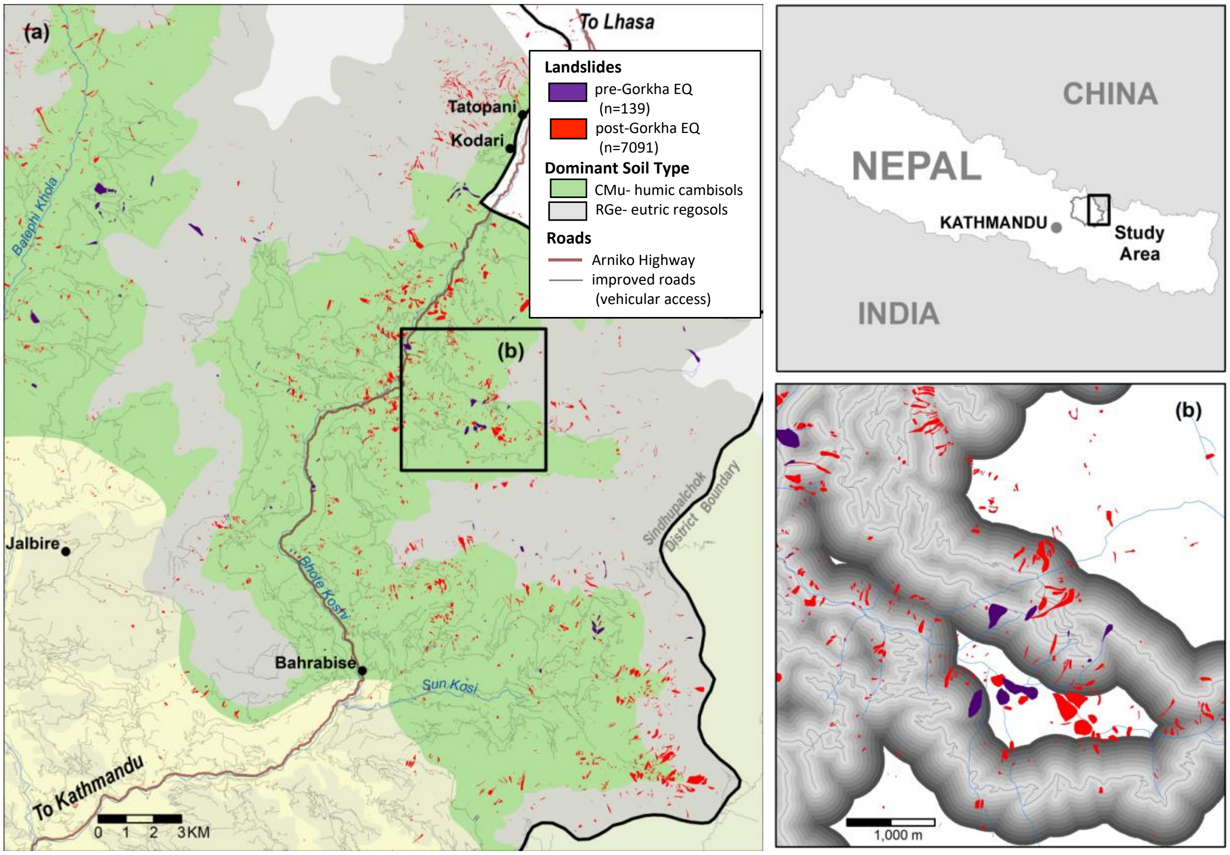

Figure 2. Roads and landslides in Sindhupalchok district, Nepal. (a) The Arniko Highway that runs between Kathmandu and Kodari at the Chinese border was heavily impacted by the 2015 Gorkha earthquake, and a dense network of informal, rural roads grows out of this main trunk road (**OpenStreetMap Contributors, 2017**). The red polygons mark the location of landslides generated during the earthquake, and the blue polygons were the landslides that were present before the earthquake (2014). Most landslides correspond with the CMu (humic cambisol) soil type as mapped by **Dijkshoorn and Huting (2009)**, however there is a higher percentage of earthquake-generated failures in the RGe (eutric regosols) soils. (b) We place buffers at 50 m intervals along the roads that can support a vehicle in the study area to determine the distribution of landslides within a given distance from the road.

To determine the spatial relationship between the landslides and roads, we sought to measure the proximity of pre- and post-earthquake slides to the roads, testing the causal relationship that has been documented by many studies (e.g. **Petley et al., 2007**; **Sidle and Ziegler, 2012**). If the percentage of pre-earthquake (monsoon) generated failures is higher than the earthquake-generated landslides, we can begin to narrow the triggering mechanisms. As the earthquake occurred near the end of the dry season, the failures would be less affected by the presence of water, therefore the location of the slides would be less influenced by features such as roads that concentrate water. Conversely, if as we expect there is a higher proportion of pre-earthquake landslides near roads, it is likely that the oversteepening and poor drainage of informal roads are indeed adding to the hazard.

To test this, we generated 20 sets of virtual landslides (10 sets based on the pre-earthquake area distribution, and 10 sets on the post-earthquake data) with areas that fall within the log-normal distribution of the existing slides. We then imported these virtual slides into a GIS and randomly placed them within the CMu and RGe soil types in Sindhupalchok district. While these data lack the complex shapes of the measured landslides (they are modelled as circular), we believe they are a reasonable first-approximation. Using the existing road network (**OpenStreetMap Contributors, 2017**), we filtered out the smallest trails and footpaths, leaving only tracks that had been improved and could likely support a vehicle (based on field observations). Finally, nine buffers were created normal to the road at 50 m intervals, and the number of landslides that have any part of the scar that intersects the buffers at the given distances were tabulated (**Fig. 3b**).

3. Results

Observations from the field and numerous previous studies (e.g. **Laban, 1979;, Sidle et al., 2006; Petley et al., 2007**) suggest a strong spatial correlation between roads and landslides, however as researchers are often traveling on roads, the sampling may be quite biased. Using satellite data, we find that the majority of non-earthquake triggered landslides occur in the soil types that support agriculture (the humic cambisols and to a lesser extent, the eutric regosols) and hence have more roads. We observe a strong signal that demonstrates the genetic relationship between agrarian development, roads, and landslides.

In Sindhupalchok district, we found that 45% (63) of the 139 pre-earthquake landslides occur within 100 m of a road, whereas only 21% (1,490) of the 7,091 landslides generated by the earthquake are within 100 m of a road. Of the randomly-generated landslides between 21% (s=0.7 for the post-earthquakes slide area distribution) and 26% (s=2.2 for the pre-earthquake slides) of the failures are within 100 m of a road (**Fig. 4**). Stated differently, there are twice as many monsoon-generated landslides near roads than the earthquake generated landslides, and twice as many than in a randomly located suite of slides with the same area distribution. The number of monsoon-triggered landslides is small by comparison- they cover a total area of 1.9 km^2 (1.2 km^2 in CMu and 0.7 km^2 in RGe) whereas the earthquake-triggered slides represent 18.4 km^2 (9.8 km^2 in CMu and 8.6 km^2 in RGe). Howeverthe average area for the monsoon-triggered slides (13,670 m^2) is much larger than the earthquake-triggered slides (2,590 m^2).

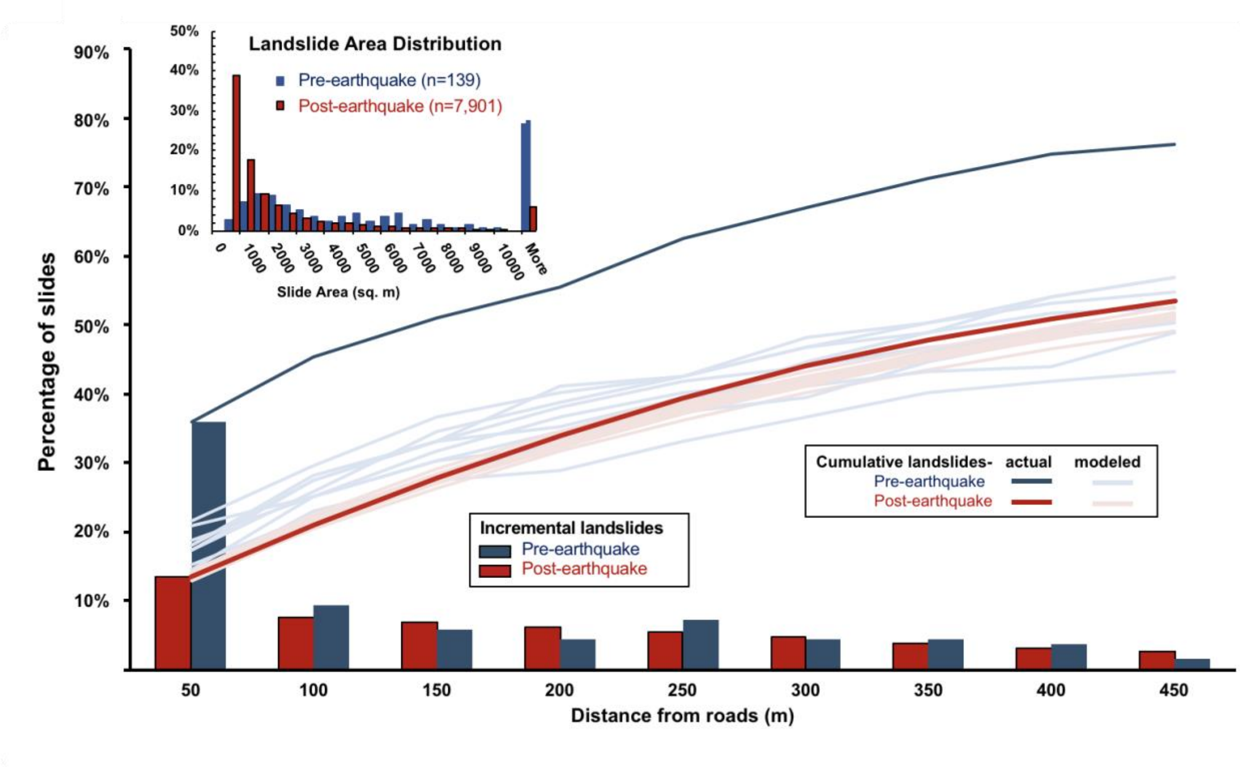

Figure 4. Distance from roads of earthquake, monsoon and randomly-generated landslides. Inset histograms show the distribution of landslide areas before and after the 2015 Gorkha earthquake. The blue and red bars are the incremental percentage of pre- and post-earthquake landslides respectively that occur a given distance from a road. The blue and red lines are the cumulative percentage of slides that occur at the given distances from the road, and the light blue and red lines are the modelled data.

The shape of the cumulative landslide distribution in **Fig. 4** holds some additional information. If there is a causative relationship between roads and landslides, we might expect to see a distinct change in slope of the cumulative slide number at increasing distances from the road that would correspond to a critical distance where the mechanical influence is reduced, and the number of landslides begins to decrease (e.g. **Brown, 1987**). This tell-tale bend in the curve is not clear in the data, possibly due to resolution issues of the smaller slides. The trend, however, is not linear- If we had a random distribution of roads across the landscape in addition to the randomly distributed landslides, we would expect to see a linear increase in the cumulative number of landslides with distance from the road. What we notice, however, is that there are less slides further away from the roads than would be expected, suggesting that the roads might be in locations that are predisposed to failure, such as near valley bottoms or ridge tops.

Many of the roads in Sindhupalchok indeed follow the major river valleys (Bhote Koshi, Sun Koshi, Balephi Khola, Indrawate and Melamchi) as well as the smaller, steep ravines that are carved into the ridges. As many landslides occur in the inner gorges of these valleys, the data might reflect this bias. However, as suggested by the distance of the randomly placed landslides from the road, the landscape is being altered by a process that is well outside of the natural variation, and observations and failure modes strongly suggests that roads are the responsible for this marked increase in slide occurrence. Regardless, as many settlements are located near these water sources, the risk to villages and transportation networks remains significant.

4. Discussion

Informal rural roads are causing dramatic changes in the physical and social landscapes of the Middle Hills region of Nepal. Although the number of slides generated by monsoon rains during a given year is vanishingly small when compared to the vast number of slides triggered by the Gorkha earthquake, they nonetheless have a substantial impact on the physical and social landscape. We show that there are twice as many landslides in the more developed areas (with its good agricultural soils and vast network of informal roads) than there would presumably be if the roads were better engineered. This concentration is due in part to the productive CMu soils in this part of the Middle Hills, along with deforestation for agriculture that likely leads to more shallow-seated landslides. Because the population in this region will soon be impacted by the improved BRI trunk road, expansion of the informal, rural transportation network is likely to grow, triggering more monsoon-rains driven failures,property loss, transportation network disruptions, and mortality.

The relationship between roads and landslides in this region gives us an idea of how important these anthropogenically-controlled slides are in shaping the landscape. The risk of roadside failures is heightened during the monsoonal rains because of slope oversteepening on the uphill side of the road and the deposition of excavated debris on the downhill side that is easily mobilised during heavy rainfall events (accentuated by runoff from the road- see Sidle et al., 2006). This combined road-rainfall effect is more acute than earthquake- generated failures in terms of percentage, if not total numbers.

These road-related failures will also impact the sediment delivery system. While this snapshot of monsoon-induced slides is small compared to those generated by the earthquake, the average size is larger and it is important to consider this additional material in annual budget calculations based on current river sediment load, and over longer periods of time. There are many new hydropower schemes following the BRI trunk road development, and they will be forced to contend with this additional sediment burden.

China's BRI fits well with the Nepali government's long-term development strategy to promote road development (**Murton, 2016; The Economist, 2017**). While the trunk roads constructed by the Chinese in the Himalaya are well-engineered, direct foreign investment and related domestic road construction has increased significantly since the end of the Maoist insurgency in 2006 (MoF, 2016), and the concern now lies in the informal roads that connect marginalised villages. With the onus of construction of rural roads in the hands of federally-funded districts, scarce funds needed for road maintenance compete with the need for investment in other sectors. **Leibundgut et al. (2016)** found that the economic impact of rural roads around Phewa Lake, Kaski district of western Nepal amounted to $117,287 USD/year in maintenance costs, forecasted to rise to $192,000 USD/year by 2030 with the current rate of road construction. Furthermore, over the last 30 years, tens to hundreds of deaths due to landslides are recorded every year (**Petley et al. 2007; DesInventar, 2016**), and yet it remains unclear how many of these failures are related to roads. Considerations of more sustainable “Green roads” that take into account local engineering geology and best practices in design, construction and maintenance (**Hearn and Shakya, 2017**) are outweighed by local communities negotiating with limited funds, short-term political agendas and ease of access to heavy equipment.

5. Conclusions

The landslides generated by the 2015 Gorkha earthquake provide an opportunity to compare the distribution of ‘natural’ failures with those triggered by humans in a landscape heavily modified by informal road construction. By comparing earthquake-generated failures with those caused by monsoonal rains beforehand as well as suites of randomly located landslides, we show that there are likely to be twice as many monsoon-generated landslides in terrain with poorly-constructed roads than would be present without roads. While these slides do not represent a much of a change in the physical systems during any given year, over time, their impact cannot be ignored. The socio-economic landscape, however, is being severely impacted by an explosion of informal roads to the point where it is hindering the development that the roads sought to bring, and killing too many people in the process. Landslides in the Anthropocene are no longer simply a function of seismology, geomorphology and climate as poorly-built roads are rapidly changing the landscape.

Better engineered roads will lead to more sustainable economic development, but these roads come with a price. Although foreign investment aids construction, maintenance costs fall on impoverished communities who must decide between access and basic services. Green solutions such as plantings on metastable hillslopes are more economically sustainable and can be implemented by community members with minimal training. There is little that can be done to control the tectonics or the climate, but economically feasible and environmentally sound adaptations will reduce losses in resources and lives.

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