Natural Hazards and Earth System Science
Authors' response to the Referee #1's comments

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Interactive comment on "Forest harvesting is associated with increased landslide activity during an extreme rainstorm on Vancouver Island, Canada" by J.N. Goetz et al.

J.N. Goetz et al.

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*Note: reply to referee's comments are in blue text and indented.

Referee #1

GENERAL COMMENTS

The theme addressed in the manuscript is of interest and relevant within the scope of landslide susceptibility analysis, in particular for areas where landslide occurrence during a specific rainfall event could be related with forest harvesting. The manuscript, in my modest opinion presents some fragilities but may be published after major revisions. Strengths: the methodology/the scientific method. Weaknesses: The type of data available to characterize the preparatory/predisposing factors to landslide occurrence.

SPECIFIC COMMENTS

SCIENTIFIC SIGNIFICANCE/ORIGINALITY:

The manuscript presents and interesting approach to evaluate landslide preparatory conditions that are responsible for landslide occurrence during a rainfall triggered landslide event. A nonparametric statistical method, the generalized additive model (GAM) is used. In my opinion one of the main contributes is the approach used to determine the regional effects of forest harvesting activities, among other variables, to landslide initiation. With respect to the preparatory factors it is worth nothing that apart of the limitations relative to some variables, such as lithology, or rainfall, an accurate approach to classify and spatially validate forest cover map is made.

SCIENTIFIC QUALITY:

The manuscript address scientific and technical subjects relevant within the scope of NHESS, nevertheless, and in the opinion of the reviewer, some drawbacks are present in the different sections of the manuscript and must be clarified, modified, eliminated or discussed in more detail.

1) In relation to the critical rainfall conditions that are responsible for landslide initiation on the Pacific Coast of British Columbia, including the mid-November 2006 landslide event, authors refer or cited: "heavy rainfall"/ "heavy precipitation" (Page 5526, line 21/22); "extreme

weather event" (Page 5528, line 16/23); "high intensity rainfall and extreme winds" (Page 5528, line 17/18); "extreme rainstorm (page 5531, line 3); "long lasting high-intensity precipitation events as observed in this study" (page 5544, line 9/10). Please clarified and define if possible how exceptional the rainfall event was. Additionally authors should explain better why select the 15 days of antecedent rainfall as the antecedent preparatory conditions responsible for the event of instability. Basically, why not 10 days or 20 days?

The storm on November 15, 2006

We have added the following paragraph to the revised manuscript (Geostatistically interpolating section) to better illustrate the significance of the storm.

> "The actual distribution of rainfall received on the island during the 15 November 2006 storm varied with aspect, elevation, location of storm cells and the wind-driven component of rain. Analysis of meteorological data by Guthrie et al. (2010b) revealed that 24-hour precipitation varied to more than 200 mm in 24 hours. Where rainfall was the only triggering factor, Guthrie et al. (2010b) determined that 88% of landslides were associated with >80 mm of rain and 70% with >100 mm of rain. In addition, ambient surface temperatures increased by 1 – 10 degrees over the same period, and coupled with strong winds, resulted in considerable snowmelt (a rain-on-snow event) for areas were precipitation alone was not responsible for the landslide response."

15 Days of antecedent precipitation

In general, debris flow and debris slides are triggered on Vancouver Island by a combination of high intensity rainstorms (Guthrie and Evans, 2004*ab*) and antecedent conditions of soil saturation (Jakob and Weatherly, 2003). As mentioned in the manuscript, given the data sources we did not have enough hourly observations (there was more station data available with daily precipitation accumulation) to estimate rainfall intensity during the 15 November 2006 storm. Consequently, we attempted to map spatial pattern of precipitation leading up to and including the storm. We interpolated the total rainfall accumulation for the most recent period of recorded continuous precipitation for Vancouver Island leading up to and including the 15 November storm (Fig. 3), which was 15 days.

The following was added to section 2.2 Geostatistically interpolating precipitation,

> "By observing daily weather station data across the island, it was determined that a two week period (2-15 November 2006) would be used to account for the antecedent conditions. These two weeks correspond to a period of continuous daily precipitation that preceded the storm."

2) To section 2 authors called "Methods". In the reviewer opinion, what are presented there are not only methods but also the description of the study area and the description and preparation of data relative to the preparatory / predisposing variables and that should be clarified / reorganized / eventually shortened. Section 2.1 is two long and part of that information should be included / adjusted in the following topics (2.2 to 2.5).

We have moved Section 2.1 to Section 2 Study Area, and have renamed Section 3 to "Materials and Methods" (it was previously section 2 Methods). The description of the study area may seem long, but we've tried to include a brief summary of morphological, climatic, and ecological characteristics that may be important for readers to understand the application of our methods, e.g. the precipitation interpolation, forest cover classification and the general conditions of landslides.

In terms of predisposing variables, the following sentence was added to section 2.4 Geology and terrain analysis,

> "Terrain analysis of topographic characteristics commonly forms the basis of quantitative landslide modelling (van Westen et al., 2008)."

Added reference:

van Westen, C. J., Castellanos, E. and Kuriakose, S. L: Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. Engineering Geology, 102, 112-131, 2008.

3) In section 2.2, page 5531, line 5, authors say that "the location of the initiation point was manually digitized where the main scarp may be expected. These initiation points were used to approximate the environmental conditions that led to slope failure". Is one point by landslide enough to determine the predisposing conditions that lead to slope instability? In my opinion this is an important drawback of the approach.

We are aware of limitations of using a single point/pixel to represent the conditions leading to landslide initiation. Some of these limitations were already mentioned in the original submission in Section 5.3 Scope and limitations (page 5547, lines 14-18):

"The spatial prediction of landslide initiation was modelled based on a single pixel per landslide, ~400 m^2 area, that was mapped in the main scarp; however, initiation of debris flows may also occur in non-head scarp regions. Ideally, the exact point of initiation would be modelled".

In general, Guthrie et al. (2010a) identified that mean landslide widths were widest at the headscarp or point of initiation, however, that width was, on average, less than 30 m wide. We feel that for a regional study such as this one, we have reasonably approximated the conditions at the initiation point.

To better describe the why we selected only one point per landslide we have added the following text to Section 2.1 Landslide inventory,

> "Only a single initiation point per landslide was mapped to provide equal treatment of landslides regardless of their size and to reduce the potential effect of spatial autocorrelation in our statistical modelling, which can occur when observations are separated by small distances (Brenning, 2005)."

Authors should provide a more detailed morphometric analysis of the landslides in order to reduce the uncertainty related to the type of landslide representation.

The focus of our analysis was to provide insights regarding the spatial patterns of landslide initiation on a regional scale across Vancouver Island (page 5528 line 24 to page 5529 line 2). Our inventory consisted of shallow landslides (max. depth of 1 m), debris flow and debris slides, which are predominantly triggered by precipitation (Guthrie, 2005). We have identified that this may not have been clearly mentioned in the previous version of the manuscript, so we have updated the revised manuscript to include the following changes,

On page 5530 lines 14 to 15 have been revised in the manuscript to the following,

> "Shallow debris flows and debris slides are the most common type of landslides occurring on Vancouver Island. These shallow landslides usually have a maximum depth of 1 meter (Guthrie, 2005). The most common triggering mechanism for these landslides is heavy precipitation; however, rapid snow melt (Guthrie et al., 2010b) and seismic activity are also known triggers of landslides in the area (Rogers, 1980; VanDine and Evans, 1992)."

On page 5530 line 25 to 26,

> "The British Columbia Ministry of Environment mapped the inventory of 638 shallow landslides for the winter of 2006-2007 (Fig. 1)."

And the following sentence was added to the end of section 2.1 Landslide inventory,

> "More detail regarding the mapping and description these landslides can be found in Guthrie et al. (2010b)."

Additionally, what is the estimated error associated to the manually determination of the landslide initial point in the expected landslide scarp?

As mentioned in the original version of the manuscript (page 5547, lines 14 to 18), identifying the actual initiation area of debris flows can be challenging because initiation can also begin in non-head scarp regions. Therefore, we cannot accurately estimate the error associated with manual mapping of landslide points; alternatively, we provide an open statement in the limitations section, which we have, on the drawback of our sampling design. Once again, we feel that for a regional study such as this one, we have reasonably approximated the conditions at the initiation point.

4) Figure 3 should be modified. The relation between daily rainfall and the altitude of the station is not easy to understand. Please reformulate the figure or consider to remove it.

Thanks for the recommendation. We have removed this figure from the manuscript.

5) Authors say in Page 5537, line 17 "the sensitivity of each model at a specificity of 90% were estimated; a specificity of 90% means that (only) 10% of the non-landslide area is misclassified as susceptible to landslides, creating false-positive predictions" and what about the false negative predictions?

The sensitivity is the true positive rate,

Sensitivity = P(prediction = landslide | observation = landslide)

and thus (1 – sensitivity) expresses the proportion of landslide locations that were incorrectly classified as "stable" locations; we believe that this is the information on false negative predictions that the reviewer requested.

6) Figure 5a was not cited in the manuscript.

Thanks, we have now cited it. We have also switched the order of Fig. 4 and Fig. 5.

7) Why in the section 3.3 the characteristics of landslides authors compare only with forest cover and forest service roads and why not with rock type or slope angle or other variables as authors state in line 13 of page 5540?

A general overview of the characteristics of the landslide initiation points vs. the landslide the non-landslide points were provided in the Table 5. We have also added the following sentence to section 3.3.

> "The majority of landslides were also initiated in volcanic rock (62%), followed by intrusive (28%), sedimentary (7%) and metamorphic rock (3%; Tab. 4)."

8) Why authors do not use soil depth or as a predisposing factor instead of rock type? What the reason for the weak association described in page 5541, line 23?

Soil on Vancouver Island is typically less than 1 m deep (http://www.env.gov.bc.ca/van-island/maps/surfical.jpg) locally derived (i.e. has not moved significantly from its bedrock source during glaciations) and is somewhat associated with bedrock type (in terms of predisposing factors).

The weak association may be related to regression dilution caused by the coarseness of the geology when represented in our input as only rock types. We mentioned this limitation in the original manuscript in Section 4.3 Scope and Limitations (line 3 to 6),

"The 'true' effect in our additive models would be expected to be larger than the estimated one. The thematic coarseness associated with our representation of geology by rock type may have also contributed to regression dilution."

9) Table 5 was not cited in the manuscript.

The citation to Table 5 (now Tab. 4) has been added to the end of first sentence on page 5539 line 25.

10) In case of the landslide susceptibility model presented by authors in Figure 11, if I understand well (page 5542, lines 22-27) the model predict in the 10 % of the area classified as more susceptible 54% of the landslide incidences. In this case the validation is done with the landslide initiation points. My question is how much of the total landslide initiation area the model is able to predict?

Landslide initiation area was not delineated in this study; however, we can provide the reviewer with estimates of model performance using the entire landslide polygon.

The resulting sensitivity at 10% false positive rate (or 90% specificity), assessed using the landslide polygons, was 45% for the model without interaction terms, and 49% for the model with interaction terms. These estimates fall within the range of sensitivity values estimated for landslide initiation points with spatial cross-validation (page

5563, Table 7). This indicates that for the most susceptibility areas, the performance of the models to predict the entire landslide polygon was not too far off from the ability to predict the initiation points. We generally expected the sensitivity estimate with the landslide polygon would be lower due to the different topographic characteristics associated with the landslide runout.

In my opinion for a complete model validation authors should use the entire landslide initiation area in the validation process. That kind of more robust validation, is fundamental to evaluate the uncertainty associated to the initial assumption that a single point is enough to determinate the preparatory conditions that turns unstable a part of a slope.

In terms of the referee's opinion towards basing the validation on a *landslide initiation area*, it should be noted that there are a wide variety of methods for validation of landslide susceptibility models that have been published in scientific literature. Some examples include validating models with landslide points (Lee et al., 2005 in Int. J. Remot. Sen; Goetz et al., 2011 in Geomorphology; Petschko et al., 2014 in NHESS); terrain units (Guzzetti et al., 2006 in Geomorphology); entire landslides (Frattini et al., 2010 in Eng. Geol.; Pradhan 2013 in Comput. Geosci.); and landslide initiation area (Van Den Eeckhaut et al., 2006 in Geomorphology). What can be concluded is that there is no one standard method for model validation in this field.

PRESENTATION QUALITY:

Overall, the manuscript is well written, well-structured and presents a clear language that is understandable and scientifically precise. The title, the abstract, the subtitles and the figures and tables captions are in general adequate. With respect to figures and tables they present generally a good quality and are almost all adequate to the purpose of the manuscript and level of the NHESS journal. Nevertheless and in respect to those items described above some comments are made in the "Scientific Quality" section and in the attached commented manuscript. Technical comments (typing errors, format, etc.) Some additionally comments regarding some problems with the references list and citations along the text are described below. For supplementary comments/suggestions see the attached file. Additionally, it is worth notice that all references are in English and a substantial number of references are accessible to the fellow scientists.

Items cited in the manuscript but not present in the References list:

Page 5530, line 12 - Guthrie and Evans (2004) – confirm if it is 2004a or 2004b;

Changed to Guthrie and Evans, 2004b.

Page 5531, line 18 - Guthrie et al (2010) – confirm if it is 2010a or 2010b;

Changed to Guthrie et al, 2010b.

Page 5532, line 6 – Goovaerts (1997) – confirm if it is 2000;

Changed to Goovaerts 2000.

Page 5532, line 19 – Swain and Davis (1978);

We removed this citation because the Maximum likelihood classifier is a common classification method such as logistic regression.

Page 5544, line 17 – Wu and Mckinnnel (1979) – confirm if it is Wu et al. 1979;

Changed to Wu et al., 1979.

Page 5544, line 25 – Guthrie et al. (2002);

Corrected to Guthrie and Evans, 2004b.

Page 5545, line 7 – Mills (1997);

Added to reference list:

Mills, K.: Forest roads, drainage, and sediment delivery in the Kilchis River watershed. Oregon Dept. of Forestry, Salem, OR, p. 21, 1997.

Page 5545, line 27 – Goetz et al. (2012);

Changed to Goetz et al. (2011).

Items not cited in the manuscript but present in the References list:

Page 5551, line 18 - Davis et al. (1978)

This was the above citation for Swain and Davis (1978). However, it has been removed as mentioned above.

Page 5551, line 23 - Dhakal and Sidle (2003)

This reference was removed from the manuscript.

Page 5551, line 29 - Foody (2004)

This reference was removed from the manuscript.

Page 5552, line 15 - Guthrie and Evans (2004b)

This reference is now cited in the manuscript (corrected citation).

Page 5553, line 17 - Lineback Gritzner et al. (2001)

This reference was removed from the manuscript.

Page 5556, line 5 - Wu et al. (1979)

Wu et al. (1979) is now cited in the manuscript. There was a correction of the citation of Wu and McKinnel (1979) to We et al. (1979).

COMMENTS FROM SUPPLEMENT MATERIAL

Page 5526, line 5: “it”, please consider replace “,” by “.”. If so, consider replace “it” by something line “to accomplish that,”.

We modified the text to the following,

“…impacts of the forest industry on landslides. Consequently, it is required that timber harvesting…”

Page 5526, line 26: “observed natural”, please consider “observed on natural”

Changed to recommendation.

Page 5528, line 20: "used by Guthrie et al., (2010b)", ahead (Page 5530, line 24) authors refer to this inventory as elaborated by the BC Ministry of Environment. This reference could be a source of misinterpretations.

We have removed the reference to the work by Guthrie et al., (2010b) here and have added a sentence to the section 2.1 landslide inventory, which directs the reader to more information regarding the landslide inventory.

Page 5529, line 16: "autumn to midwinter", please also refer to what months.

We have added the following, "which is generally from October to March."

Page 5531, line 18: "Guthrie et al., 2010", 2010a or 2010b?

Changed to Guthrie et al, 2010b.

Page 5532, line 19: "Swan and Davis, 1978", reconsider re-locate the Swan and Davis, 1978 reference. Maybe after (MLC)?

We removed this citation because the Maximum likelihood classifier is a common classification method such as logistic regression.

Page 5536, line 14: "5 variables", how many classes for each variable?

In the GAM it is not required to categorize continuous variables, such as you would have to create classes when using the weights of evidence method. To clarify this to the readers we have done the following modification,

"(5 quantitative predictors)"

Page 5539, line 26: "landslides", this is referred to the total landslide area or only to the initiated landslide area? Please make clear along the 3.3 section.

We have made the following modification,

"Although closed forest had the largest cumulative area affected by landslides (calculated from the polygons representing the entire landslide area; 2.3 km^2)"

Page 5565: "white-dotted polygon lines outline the landslide shape", this white-dotted polygon lines are not enough contrasted from the Sold-circle points that represents the landslides. Please consider another type of line to represent the landslide limit. What about a different representation format for debris slides and debris flows?

We have added colour to this figure to more clearly identify the locations of landslide initiation.