Exploring the relationship between avalanche hazard and run-list terrain choices at a helicopter skiing operation

Author's response

Reto Sterchi, Pascal Haegeli
July 15, 2019

Dear Margreth Keiler

Thank you for taking the time to read our manuscript in detail and handle it as editor. We have incorporated the comments brought up by the three referees as well as your own suggested technical items into a revised version of the manuscript.

In addition to these items, we edited the entire manuscript in detail to improve its quality including grammar and rewording of individual sentences to improve readability for the reader.

The following pages of this PDF provide an overview of all changes and include

- a collection of our point-by-point responses to the referees and
- a document including track-changes of our manuscript.

Best regards,
Reto Sterchi

Exploring the relationship between avalanche hazard and large-scale terrain choices at a helicopter skiing operation – Insight from run list ratings

Response to Anonymous Referee #1

Reto Sterchi, Pascal Haegeli
July 6 26, 2019

We would like to thank the reviewer for taking the time to read our manuscript in detail and provide constructive feedback. The following sections describe our response to the comments raised by the referee and outline the changes we made to the manuscript to address these concerns.

1 Title

Review (Reviewer #3 made the same comment)
[…] The tile uses the expression "large-scale"; I recommend the use of "regional" here so that it becomes clear that a large scale (1:10,000 or so) is meant, or "detailed assessment" if this should be the focus, but not – as this expression is quite often also used in NHESS – a nation-wide assessment. […]

Response to the review and changes made to the manuscript
We agree that the expression "large-scale" is not sufficiently specific for describing the spatial scale of our analysis. However, we feel that the proposed "region" is ambiguous as well. Since the scale of the guides' process refers to individual runs, we believe that replacing the expression "large-scale terrain choices" with "run list terrain choices" is most appropriate. To address the reviewer's concern, we made the following changes (highlighted in green):

Title
"Exploring the relationship between avalanche hazard conditions and run-list terrain choices at a helicopter skiing operation"

2 Acceptable risk level

Review
[…] In the abstract as well as in the main text body the authors repeatedly address the term "acceptable risk level", from the overall scientific discussion and concept behind risk and vulnerability, I am wondering what exactly is meant by "acceptable" (death rates below a certain percentage? Number of ski runs without avalanche accident?) and if some explanatory sentences could help here to avoid confusion. […]

Response to the review and changes made to the manuscript
Whereas acceptable avalanche risk levels have explicitly been defined in land use planning (e.g., 1 in 30 years, 1 in 100 years, and 1 in 300 years avalanche risk maps), they have not been defined in backcountry and mechanized skiing. We intended to us the term "acceptable" in a more qualitative way to express that operations do their best to avoid avalanche incidents while acknowledging that the activity is inherently risk and not all of the risk can be eliminated. However, considering this review, we

changed the following instances, where we describe terrain choices intended to reduce the risk to an acceptable level as "appropriate terrain choices" (changes highlighted).

Page 1, line 10ff:
[…] Using a large data set of over 25 000 operational run list codes from a mechanized skiing operation, we applied a general linear mixed effects model to explore the relationship between ~~acceptable~~ skiing terrain that is deemed appropriate (i.e., status open) and avalanche hazard conditions. […]

Page 3, line 3ff:
[…] The objective of our study is to advance our understanding of the professional avalanche risk management process by quantitatively examining the relationship between ~~acceptable~~ skiing terrain appropriate (i.e., open or closed for guiding) and avalanche hazard conditions at the run scale using historic avalanche hazard assessments and run list ratings from a commercial helicopter skiing operation. […]

Page 20, line 1ff:
[…] For example, explicitly including the likelihood of avalanches and destructive size parameters of the existing avalanche problems in the run list model has the potential to extract more detailed information about the relationship between the avalanche hazard situation and characteristics of runs with ~~acceptable~~ appropriate skiing terrain. […]

Page 20, line 11ff:
[…] Using a large, multi-seasonal dataset of operational run list choices from a mechanized skiing operation, we applied a general linear mixed effects model to quantitatively explore the relationship between avalanche hazard conditions and ~~acceptable~~ appropriate skiing terrain numerically for the first time. […]

Page 20, line 29ff:
[…] For the first time, the effect of avalanche hazard has been isolated from the influence of other factors such as the run list code the day before and the effect of recent skiing. Properly isolating these effects is critical for describing the relationship between avalanche hazard and ~~acceptable~~ appropriate terrain in a meaningful fashion. […]

3 Operation vs. Operator

Review

[…] The authors address multiple times the "mechanised skiing operation" but are using data from one operator; maybe the wording could be "mechanised skiing operator" to avoid confusion (e.g., page 1, line 11; page 20, line 11). […]

Response to the review and changes made to the manuscript

The term "operator" usually refers to the actual person that operates (and potentially owns) a mechanized skiing operation. We believe that keeping the term "operation" is more appropriate since our study analyses the run list risk management decisions of an entire organization. We did not make changes to the manuscript.

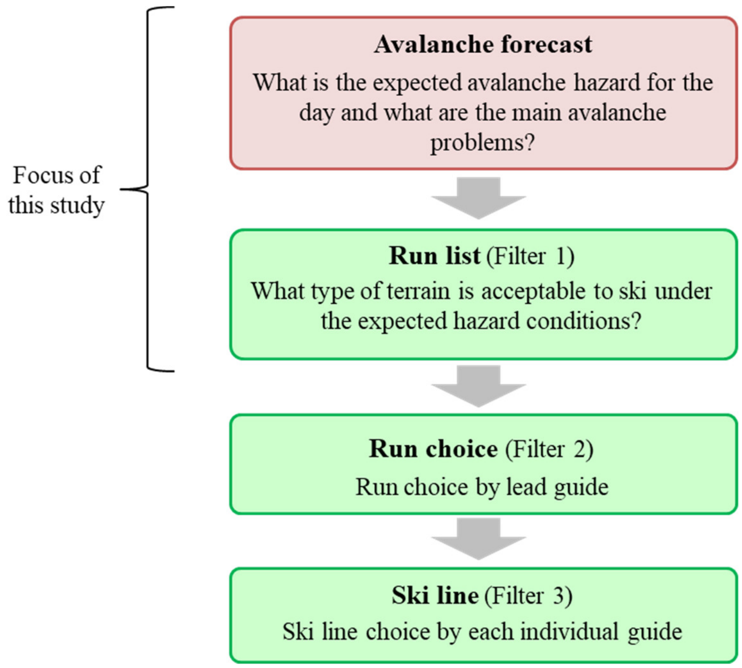
4 Illustration of risk management process

<u>Review</u>

[…] On page 2, lines 1-22 the author describe the procedure of assessing avalanche hazard and establishing the run list, it would be useful to underpin this by a Figure showing the different steps by e.g., boxes and arrows in between. […]

<u>Response to the review and changes made to the manuscript</u>

Thank you for highlighting this issue. We believe that a figure will help illustrating the entire process as well as the focus of our study and propose the following figure.



Caption: Hierarchical terrain selection process in mechanized skiing in Canada.

5 References

<u>Review</u> (Reviewer #3 made the same comment)

[…] Please check references for updates, and provide a doi for those references that are in press. […]

<u>Response to the review and changes made to the manuscript</u>

Thank you for highlighting this. The paper is in now press and we updated the reference accordingly.

Walcher, M., Haegeli, P., and Fuchs, S.: Risk of Death and Major Injury from Natural Winter Hazards in Helicopter and Snowcat Skiing in Canada, Wild. Environ. Med., https://doi.org/10.1016/j.wem.2019.04.007, 2019.

Exploring the relationship between avalanche hazard and large-scale terrain choices at a helicopter skiing operation – Insight from run list ratings

Response to Anonymous Referee #2

Reto Sterchi, Pascal Haegeli
July 6, 2019

We would like to thank the reviewer for taking the time to read our manuscript in detail and provide constructive feedback. The following sections describe our response to the comments raised by the referee and outline the changes we made to the manuscript to address these concerns.

1 Methods: Description of avalanche problems with examples

Review

[…] Page 4, lines 20 to 31: this content does not really belong to the description of the data. In my opinion it also could be skipped. […]

Response to the review and changes made to the manuscript

The avalanche problem types are a crucial part of the Conceptual Model of Avalanche Hazard (CMAH) and the data set used for our study. However, we agree that a brief description of the importance of identifying avalanche problems and their connection to terrain choices might be enough information so that readers can understand what we did in our study and the essence of the results but can refer them to Statham et al (2018) for the details. We shortened and changed the text of lines 20-31 as following.

[…] "While some avalanche problems are of relatively short duration and can be managed easily by avoiding specific terrain features within runs (e.g., wind-loaded slopes when a wind slab avalanche problem is present), others can persist for weeks, even months and require a more conservative risk management approach that includes a broader range of terrain (Haegeli et al., 2010; Statham et al., 2018)." […]

2 Methods: Encoding the nature of the ski terrain

Review

[…] Page 5, lines 12 to 30: This part rather belongs to the introduction and could be adapted in a way to emphasise the motivation for this study.

Response to the review and changes made to the manuscript

A similar comment was made by reviewer #3. We shortened and changed the text of lines 11-30 as following.

Page 5, line 11ff

[…] To identify meaningful patterns between avalanche hazard and terrain choices numerically, it is critical to encode the nature of the available ski runs in a concise, but insightful way. To comprehensively capture of complex nature of entire ski runs into our model in a way that reflects how professional guides perceive them, we used the approach introduced by Sterchi and Haegeli (2019), which groups the ski

runs into operation-specific terrain classes based on multi-seasonal patterns in run list ratings (i.e., revealed terrain preferences). In comparison to existing terrain classification systems with small numbers of universal terrain classes (e.g., ATES; Statham et al., 2006; Campbell and Gould, 2013), Sterchi and Haegeli's approach identifies high-resolution, operation-specific ski run hierarchies based on multi-seasonal patterns in run list ratings (i.e., revealed terrain preferences). Sterchi and Haegeli first identified groups of ski runs by clustering similarly coded ski runs over the course of several winter seasons. Subsequently, they arranged the identified groups into a hierarchy that ranges from runs that are almost always open to runs that are only open when conditions are favourable. To better understand the nature of the revealed ski run classes, the authors had a senior lead guide at each participating operation provide a comprehensive but structured description of their ski runs with respect to access, type of terrain, skiing experience, operational role, hazard potential, and guide-ability. Since this ski run classification is based on past operational risk management decisions, it reflects the local terrain expertise and avalanche risk management practices in the context of the available terrain and local snow and avalanche climate conditions (Sterchi and Haegeli, 2019). Thus, this approach represents a more meaningful characterization of ski run classes to analyze professional terrain choices in mechanized skiing operations. […]

3 Methods: Avalanche sizes

Review

[…] Page 5, line 18: Better talk about avalanche sizes on figures 1-3 e.g. because the wording has changed in the European classification.

Response to the review

Thanks for highlighting this inconsistency in avalanche size description.

Changes made to the manuscript

To address the reviewer's concern, we made the following changes (highlighted in green):

[…] and the potential of being seriously injured or deeply buried by avalanches of smaller or equal to size 3. […]

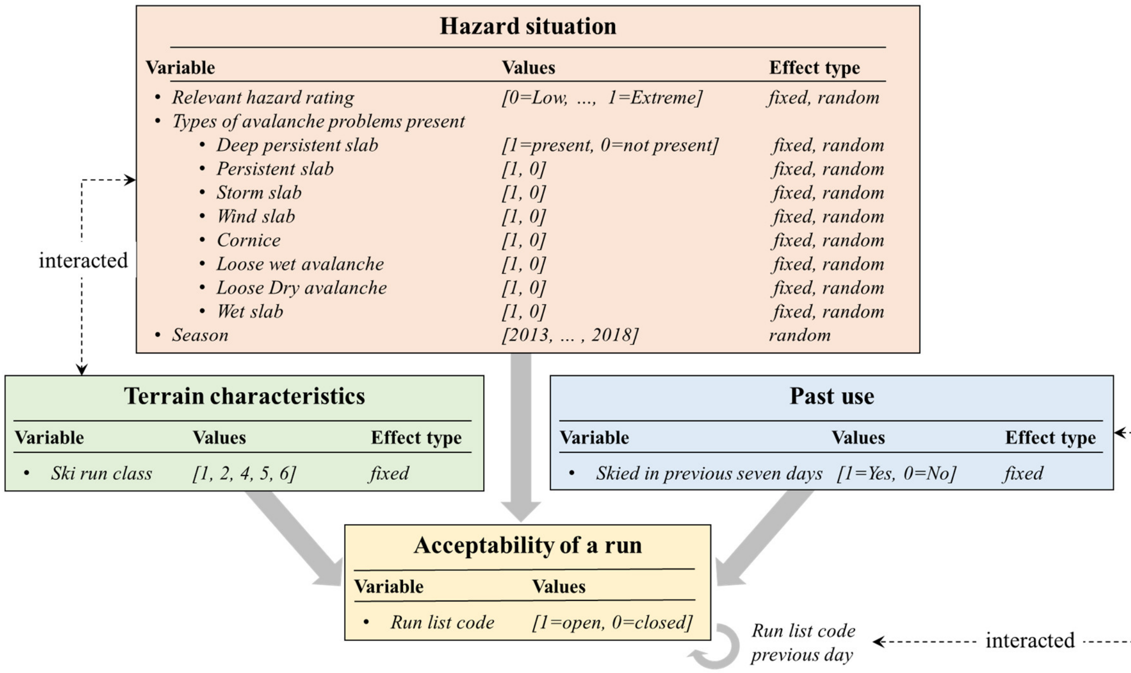
4 Methods: Model description

Review

[…] Page 8/9: The explanatory variables and interactions are well explained but could be summarized in a table for a better overview. Further the illustration and explanation of the model is not clear. Better describe model with a formula than with figure 3. Or change Fig.3 for better understanding.

Response to the review and changes made to the manuscript

Thank you for pointing that out. After considerable reflection, we believe that a formula would not provide much clarification of the model due to the many variables and interactions involved. However, we believe that structuring the figure in a more table-like layout with additional variable information on could help to overcome the highlighted shortcomings. To address the reviewer's concern, we made the following changes to the figure.



5 Methods: Description of result presentation

Review

[…] Page 10, lines 17 to 24: This section rather fits to the results chapter and explains Fig. 4. […]

Response to the review and changes made to the manuscript

We agree that this description of the graph can also be moved into the results section and moved it into section 3.1 where we present figure 4.

6 Results: Description of parameter estimate

Review

[…] Page 11, line 8: Mention value in the text (e.g. in brackets) for better understanding. […]

Response to the review and changes made to the manuscript

Thanks for pointing out this inconsistency. To address the reviewer's concern, we added the parameter estimates on several instances throughout the results section.

7 Results: Falsely referenced table

Review

[…] Page 15, line 28: Table 2 not 1 […]

Response to the review

Thanks for highlighting this typo. We made the following changes (highlighted in green):

Page 15, line 28

[…] This means that runs in severe alpine terrain are much less likely to be open during times when Deep persistent slab avalanche problems are a concern (OR=0.10 and OR=0.07, respectively, Table 2) […]

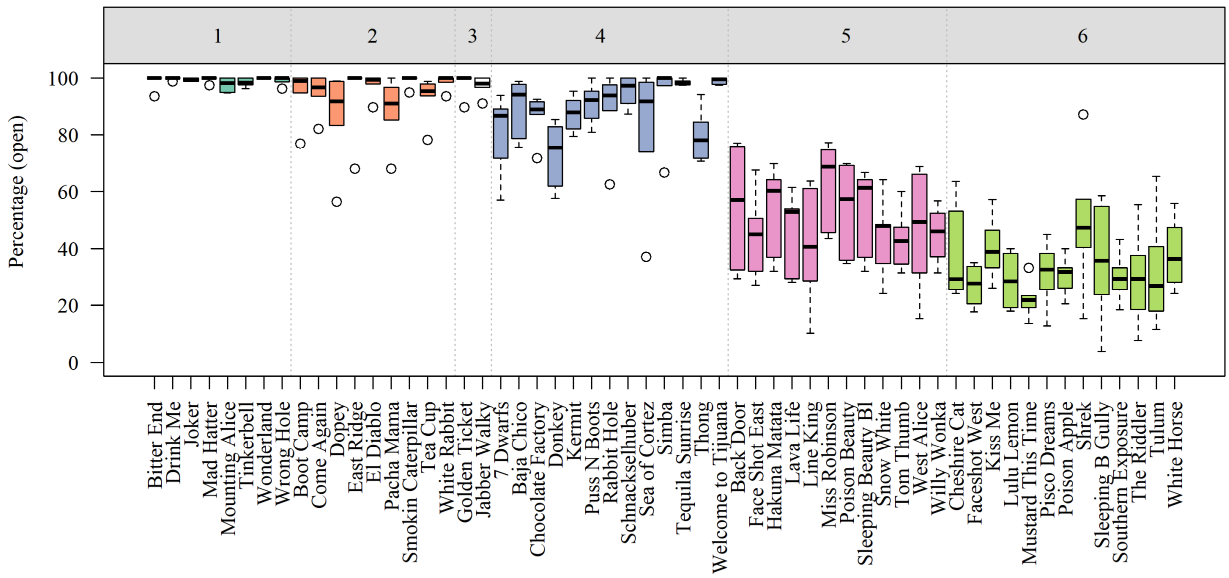
8 Figures: Size of figure 2

Review

[…] Fig. 2: Is rather small. Could be expanded to entire page width. […]

Response to the review and changes made to the manuscript

A similar comment was made by reviewer #3. We agree with the reviewers and propose to increase the size of the figure and will use the entire width of the page for the figure.



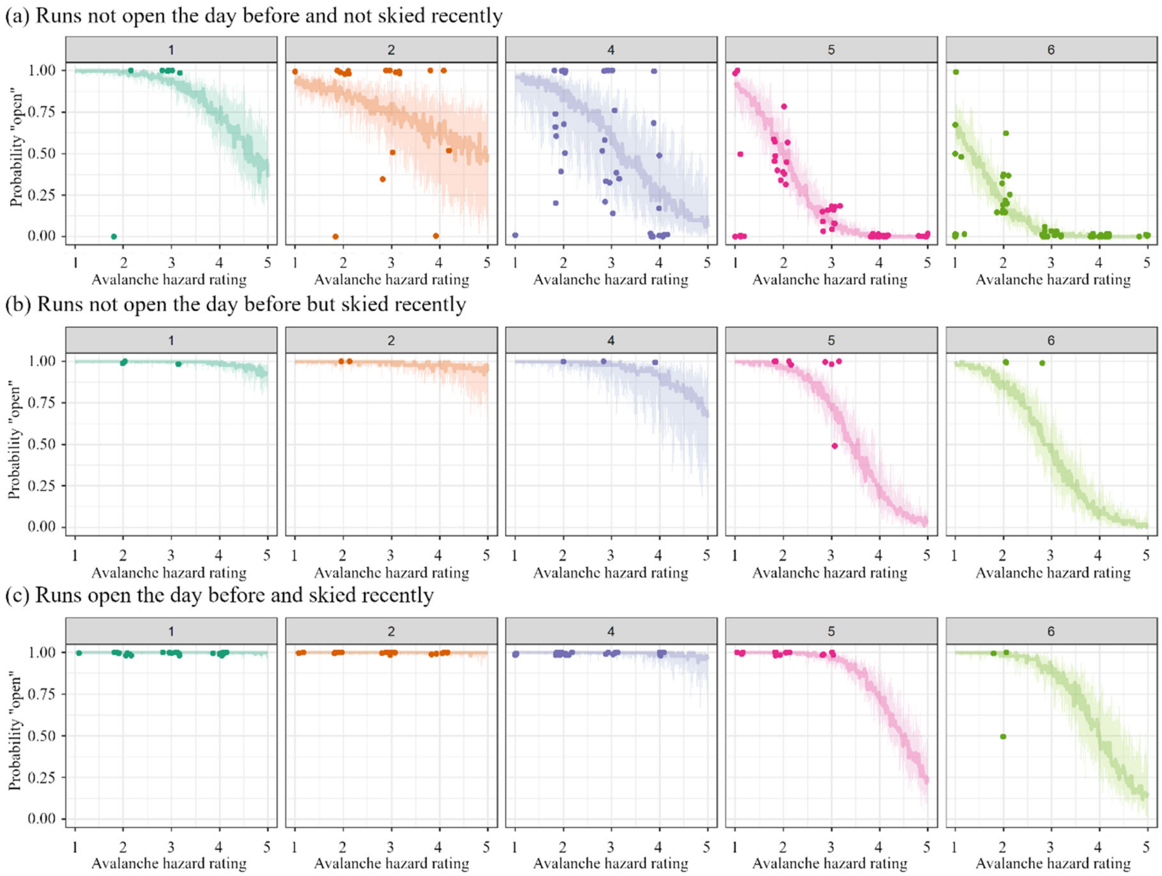
9 Figures: Figure 4

Review

[…] Shading in graphs is not clear. What is 50%, 80% and 95%. Better reduce to 2 percentages. Label of x-axis is missing. Mention avalanche hazard as x-axis in caption text. […]

Response to the review and changes made to the manuscript

Thank you for pointing out this shortcoming of Figure 4. We agree that the including three different percentages is too much and makes the different shadings difficult to distinguish. To address the reviewer's concern, we will only use two percentages (50% and 95%). We also addressed the missing label of the x-axis and mentioned the axis in the caption text (highlighted in green).



[…] Figure 4: Probabilities of ski runs being open for Storm slab avalanche problems *shown for increasing hazard levels* *with (a) a scenario where ski runs were neither open previously nor skied recently, (b) a scenario where runs were not open the day before but recently skied, and (c) a scenario where runs were open the day before and recently skied. The visualizations include probability intervals of* *50% and 95%* *for each ski run class as a whole based on 50 draws from the posterior distribution. Average daily percentages of open runs per ski run class are plotted as points where observations for this scenario exist in the dataset. […]*

10 Figures: Figure 5

Review

[…] Fig. 5: Figure is to small and not readable. Label of x-axis is missing. […]

Response to the review and changes made to the manuscript

Thank you for point this out. We replaced this figure in response to a comment of reviewer #3.

11 Technical corrections

Review

[…] Page 16, line 5: Typo: "…, the influence of different …"[…]

Response to the review and changes made to the manuscript
Thank you for point this out. We changed the sentence accordingly.

Review
[…] Page 16, line 12: Typo: "…, they can gain size and speed." *[…]*

Response to the review and changes made to the manuscript

Thank you for point this out. We changed the sentence accordingly.

Review
[…] Page 19, line 4: Typo: "s" is missing either for "results" or "shows" *[…]*

Response to the review and changes made to the manuscript

Thank you for point this out. We changed the sentence accordingly ("results").

Review
[…] Page 19, line 12: Typo: "… method that is able to account for …" *[…]*

Response to the review and changes made to the manuscript

Thank you for point this out. We changed the sentence accordingly.

Review
[…] Page 21, line 5: Typo: "… envision these decision aids to …" *[…]*

Response to the review and changes made to the manuscript
Thank you for point this out. We changed the sentence accordingly.

Exploring the relationship between avalanche hazard and large-scale terrain choices at a helicopter skiing operation – Insight from run list ratings

Response to Anonymous Referee #3

Reto Sterchi, Pascal Haegeli
July 6, 2019

We would like to thank the reviewer for taking the time to read our manuscript in detail and provide constructive feedback. The following sections describe our response to the comments raised by the referee and outline the changes we made to the manuscript to address these concerns.

1 Title

Review (Reviewer #1 made a related comment)
[…] Consider "Exploring the relationship between avalanche hazard conditions and run-list terrain choices at a helicopter skiing operation". A little shorter and the phrase "large-scale terrain choices" is ambiguous. […]

Response to the review and changes made to the manuscript
Thank you for this comment. Reviewer #1 had similar concerns about the term "large-scale". We think the proposed modification is an excellent suggestion that makes the title clearer.

Adapted title: "*Exploring the relationship between avalanche hazard conditions and run-list terrain choices at a helicopter skiing operation*"

2 Reference: Walcher et al.

Review (Reviewer #1 made a related comment)
[…] Page 1 Line 24-25: Please check if there is a more recent reference. Walcher et al. (under review) or Walcher (Master thesis) perhaps would be more appropriate […]

Response to the review and changes made to the manuscript
Thank you for highlighting this. The paper is in now press and we updated the reference accordingly.

Walcher, M., Haegeli, P., and Fuchs, S.: Risk of Death and Major Injury from Natural Winter Hazards in Helicopter and Snowcat Skiing in Canada, Wild. Environ. Med., https://doi.org/10.1016/j.wem.2019.04.007, 2019.

3 Introduction: Additional methods of controlling avalanche hazard

Review
[…] Page 1 Line 27 - 29: Consider mentioning that operations use direct control of avalanche hazard through the use of explosives and strategic control of future avalanche hazard through "run maintenance" skier traffic. […]

Response to the review and changes made to the manuscript
Thank you for pointing this out. We agree with the reviewer that it is worth mentioning that depending

on the operational practices, the use of explosives or the strategic control of the snowpack through skier traffic is common. To address the reviewer's comment, we made the following changes (highlighted in green):

Page 1, Line 27ff
[…] Operations manage this risk by continuously assessing the local avalanche hazard conditions and carefully choosing appropriate terrain and travel procedures to limit their exposure to avalanche hazard and keep the residual risk at an acceptable level while still providing a high-quality skiing experience. <u>Some operations may use explosives to directly control avalanche hazard or purposely ski individual ski runs to control future avalanche hazard by modifying the local snowpack (often referred to as "run maintenance").</u> […]

4 Introduction: Hazard forecast only for first couple runs

<u>Review</u>
[…] Page 2 Line 3-5: General comment for reference, most mechanized guiding teams will produce the avalanche hazard forecast for the first run or two of the day rather than for the full day. i.e. "what is the avalanche hazard as we head out the door?". This hazard evaluation is then updated as new information is obtained throughout the day. […]

<u>Response to the review and changes made to the manuscript</u>
Thank you for commenting that this sentence needs clarification. We fully agree with the comment of the reviewer and are proposing the following changes (highlighted in green) to better highlight the evolutionary character of the hazard assessment and run selection.

Page 2, Line 3ff
[…] The daily process starts with a morning meeting where the guiding team assesses the current hazard conditions and produces a <u>first</u> large-scale avalanche hazard forecast across the entire tenure <u>based on the previous day's experiences and the observed overnight changes.</u> This <u>initial</u> hazard assessment is the foundation for the <u>day's</u> "run list", which represents the first terrain elimination filter. In this step, the guiding team goes through their inventory of predefined ski runs and collectively decides for each run whether it is open or closed for skiing with guests under the expected avalanche hazard conditions. It is important to note that depending on the nature of the operation, the scale of ski runs can range from tightly defined ski lines to areas the size of a medium ski resort. However, regardless of their size, the nature of ski run is consistent enough that they represent meaningful decision units at this stage of the risk management process. The large-scale, consensus-based run list that emerges from the morning meeting sets the stage for the skiing program of the day. Over the course of a skiing day, <u>the avalanche hazard assessment</u> is refined and adapted in response to direct field observations <u>and runs that are skied are chosen from the run list accordingly.</u> […]

5 Introduction: Description of hazard assessment

<u>Review</u> (Reviewer #2 made a related comment)
[…] Page 2 Line 3 - 5: Consider adding brief details about 'avalanche problems' as these are more impactful on the run list than the avalanche hazard rating. […]

<u>Response to the review and changes made to the manuscript</u>
We intentionally speak of avalanche hazard in general here in the introduction while we go into the

details of how avalanche hazard is characterized with avalanche problems and an avalanche rating in the methods section where we describe our data set. We did not make changes to the manuscript in response to this comment. However, please note that we revised the description of the avalanche problems included in our data set in response to Reviewer #2 (comment 1, manuscript page 4, lines 21ff).

6 Introduction: General wording of run list codes

Review

[…] Page 2 Line 7: Please change "...open or closed for skiing with guests..." to "...open or closed for guiding with guests...". Note, disregard this if the specific operation (Northern Escape) uses the stated nomenclature. […]

Response to the review and changes made to the manuscript

Thanks you for pointing out this inconsistency in the description of the codes in the methods section. To address the reviewer's comment, we made the following changes (highlighted in green):

[…] In this step, the guiding team goes through their inventory of predefined ski runs and collectively decides for each run whether it is open or closed for guiding with guests under the expected avalanche hazard conditions. […]

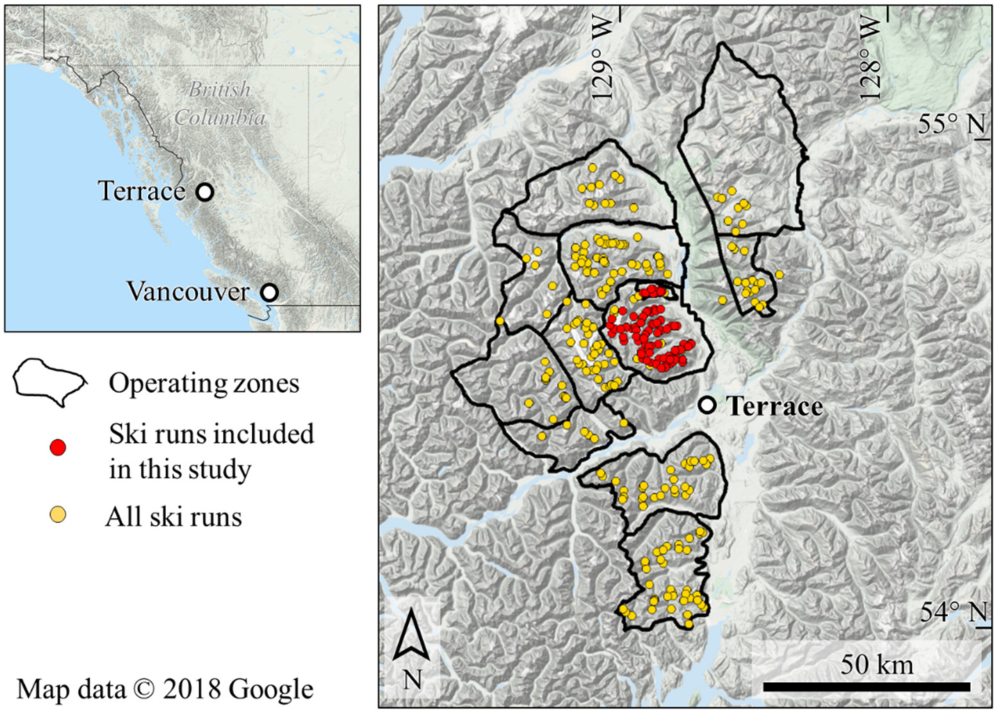
7 Figure 1: North arrow and coordinates

Review

[…] Page 3 Figure 1: Please add direction indication (i.e. north arrow) and coordinates. […]

Response to the review and changes made to the manuscript

Thank you for pointing out this cartographic flaw. To address the reviewer's comment, we changed the figure accordingly.



8 Data set: Use of yellow coding of runs

<u>Review</u>

[…] Page 4 Line 1 - 8: Does NEH use yellow coding of runs that can be opened in the field after a specific condition has been confirmed? If so, could you comment on how this might affect the results of the study? […]

<u>Response to the review and changes made to the manuscript</u>

Northern Escape does not use yellow codes to indicate that runs could be opened in the field conditional on specific conditions observed. No changes were made to the manuscript.

9 Data set: Avalanche size classification

<u>Review</u>

[…] Page 5 Line 4: Delete "for a given path". Avalanche size classification relative to the path size is the US relative scale size definitions and the Canadian size definitions are referenced […]

<u>Response to the review and changes made to the manuscript</u>

We agree with the comment and deleted "for a given path".

Page 5, line 3ff:

[…] Destructive size is assessed according to the Canadian avalanche size classification (Canadian Avalanche Association, 2014) on a scale ranging from 1.0 (relatively harmless for people) to 5.0 (largest snow avalanche known ~~for a given path~~, which 5 could destroy a village or a large forest area of approximately 40 hectares). […]

10 Data set: Description of avalanche hazard levels

Review

[…] Page 5 Line 8 - 10: Consider deleting the sentence "While this hazard ... ". This is not directly relevant to the study and can be discovered through the references. […]

Response to the review and changes made to the manuscript

We agree with the reviewer that this specification can be omitted from the description of the hazard rating applied by NEH. We made the following changes to the manuscript (additions and deletions highlighted in green and red respectively) to address this comment.

Page 5, line 7-10:

[…] The hazard assessments for each elevation band are concluded by summarizing the overall hazard level that emerges from the combined avalanche problems with a single hazard rating on an ordinal scale from 1 (least hazardous) to 5 (most hazardous; Canadian Avalanche Association, 2015).~~While this hazard scale is derived from the North American Public Avalanche Danger Scale (Statham et al., 2010), it is distinctly different as it does not include the common signal words (i.e., Low, Moderate, Considerable, High, and Extreme) or travel advice.~~ […]

New reference for the hazard rating:

Canadian Avalanche Association: Avalanche Hazard Rating Scale. InfoEx Advisory Committee. Available at http://infoexhelp.avalancheassociation.ca/wiki/Hazard_rating_definition_table (last access: 3 July 2019), 2015.

11 Data set: Description of terrain classification

Review

[…] Page 5 Line 12 - 28: Please consider deleting these lines and re-wording. The background information on avalanche terrain classification, while interesting, is not very relevant. In my opinion, it would be more beneficial to focus on the methods used in this study to encode the runs and the benefits of these methods. The Wakefield et al., 2018; and Sterchi and Haegeli, 2019; studies are appropriate to describe and to describe how they were applied here in this study. […]

Response to the review and changes made to the manuscript

A similar comment was made by Reviewer #2. We substantially shortened and changed the text of lines 11-30 as following.

Page 5, line 11ff

[…] To identify meaningful patterns between avalanche hazard and terrain choices numerically, it is critical to encode the nature of the available ski runs in a concise, but insightful way. To comprehensively capture of complex nature of entire ski runs into our model in a way that reflects how professional guides perceive them, we used the approach introduced by Sterchi and Haegeli (2019), which groups the ski runs into operation-specific terrain classes based on multi-seasonal patterns in run list ratings (i.e., revealed terrain preferences). In comparison to existing terrain classification systems with small numbers of universal terrain classes (e.g., ATES; Statham et al., 2006; Campbell and Gould, 2013), Sterchi and Haegeli's approach identifies high-resolution, operation-specific ski run hierarchies based on multi-seasonal patterns in run list ratings (i.e., revealed terrain preferences). Sterchi and Haegeli first identified groups of ski runs by clustering similarly coded ski runs over the course of several winter seasons.

Subsequently, they arranged the identified groups into a hierarchy that ranges from runs that are almost always open to runs that are only open when conditions are favourable. To better understand the nature of the revealed ski run classes, the authors had a senior lead guide at each participating operation provide a comprehensive but structured description of their ski runs with respect to access, type of terrain, skiing experience, operational role, hazard potential, and guide-ability. Since this ski run classification is based on past operational risk management decisions, it reflects the local terrain expertise and avalanche risk management practices in the context of the available terrain and local snow and avalanche climate conditions (Sterchi and Haegeli, 2019). Thus, this approach represents a more meaningful characterization of ski run classes to analyze professional terrain choices in mechanized skiing operations than existing terrain classification systems which have small numbers of universal terrain classes (e.g., ATES; Statham et al., 2006; Campbell and Gould, 2013) or focus primarily on standard terrain characteristics such as slope incline, slope shape, elevation, aspect, and vegetation density (e.g., Hendrikx et al., 2016; Thumlert and Haegeli, 2018). […]

12 Data set: Terrain descriptors

Review

[…] Page 6 Line 19 - 20: Please re-word or delete "or non-glaciated or glaciated alpine". […]

Response to the review and changes made to the manuscript

We simplified this sentence (changes highlighted in red):

Page 6, Line 19f:
[…] Most of the skiing is through open slopes at tree line, open canopy snow forest below tree line, ~~or~~ non-glaciated or glaciated alpine. […]

13 Figure 2: Size and caption

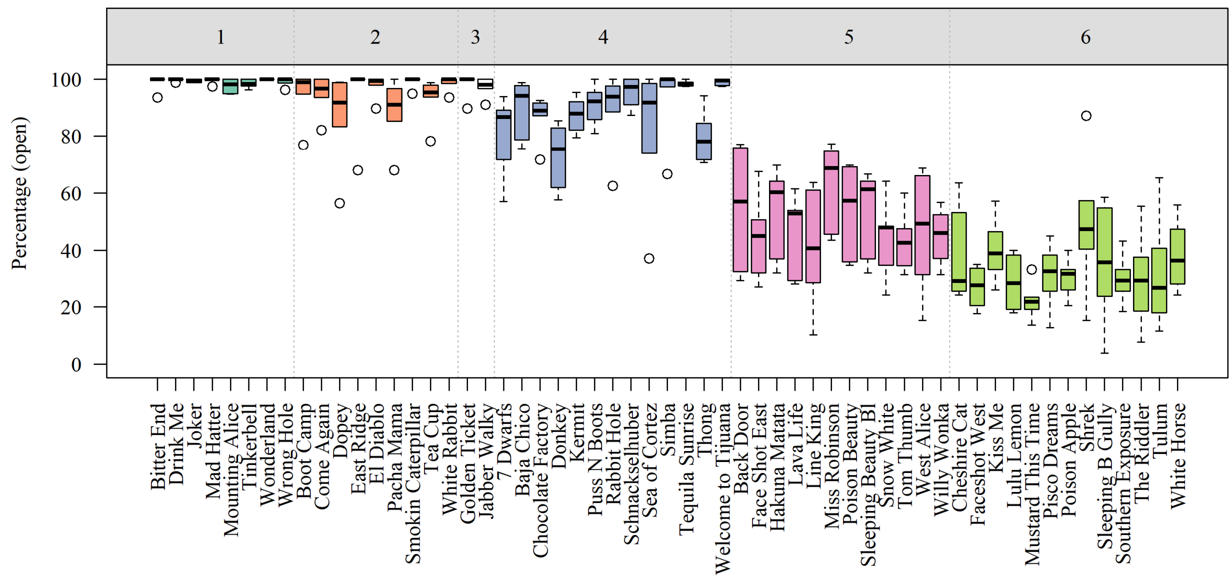
Review

[…] Page 6 Figure 2: Increase the size of the Figure with the aim to increase the font size. It is difficult to read the run labels. […]

[…] Page 6 Figure 2 caption: Change the word "average" to "boxplots" or something similar that describes what data are shown. […]

Response to the review and changes made to the manuscript

A similar comment was made by Reviewer #2. In response we increased the size of this figure to enhance readability. We also changed the caption of the figure (changes highlighted in green).



Caption:
Figure 2: Boxplot of average seasonal percentages of run code 'open' for the 57 ski runs during the six seasons 2012/13 to 2017/18 with the six identified classes of similarly managed ski runs (Sterchi & Haegeli, 2019). Due to the small group size and their outlier characteristics, the two runs of Class 3 were not included in the present analysis.

14 Data set: Table with terrain characteristics

Review

[…] Page 6 Line 18 to Page 7 Line 14: Consider using a table to describe the characteristics of the 6 classes of runs. Consider example photographs of the terrain from each code as these would greatly enrich the understanding of the terrain types. […]

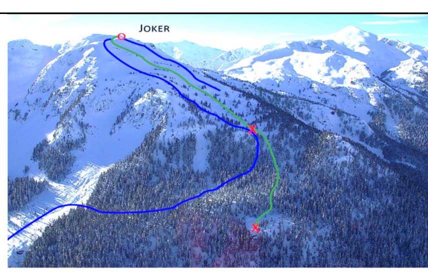
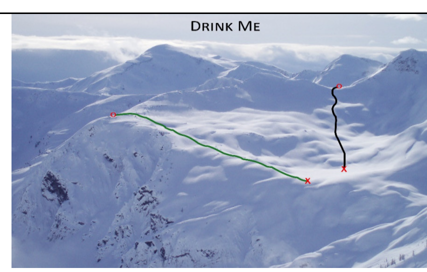
Response to the review and changes made to the manuscript

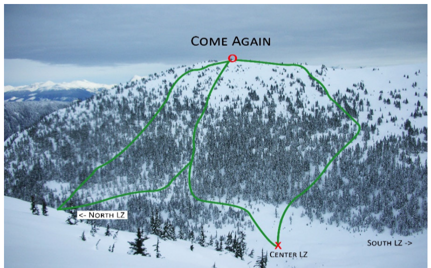
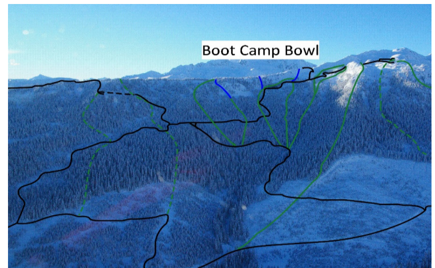
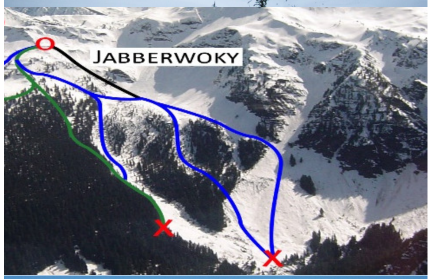
We believe that providing photos of typical runs for each group add value to the presentation of the terrain characteristics and we added the following table to the manuscript:

Page 6, line 10:

[…] Table 1 provides an overview of the general character of the NEH ski runs included in this study. […]

Caption for Table 1: Photos of typical ski runs included in this study. All photos reproduced with permission of NEH.

Class	Number of runs	Typical ski runs	
Class 1	8		

Class 2	9		
Class 3	3		
Class 4	13		
Class 5	12		
Class 6	13		

15 Data set: Descriptor “life-changing”

Review

[…] Page 7 Line 9: Consider re-wording "Life-changing". […]

Response to the review and changes made to the manuscript

The description of the terrain classes is based on the study by Sterchi and Haegeli (2019). They used a survey that was developed in collaboration with senior lead guides to characterize and describe different terrain types. Since the descriptor “life-changing” originates form this survey, we did not make any changes to this manuscript.

16 Data set: Number of avalanche problems

Review

[…] Page 8 Line 27: Page 4 Line 15 details that the CMAH uses nine avalanche problems. It appears as though you removed glide-slab problem from the analysis, which seems appropriate, however could you provide the rational for this? […]

Response to the review and changes made to the manuscript

Thank you for commenting in this inconsistency. Since NEH does not specify glide slab avalanches, we only have eight avalanche problems in our dataset. We propose the following amendments for the manuscript where we described the our model(highlighted in green):

Page 8, Line 22ff *(original manuscript)*

[…] Avalanche hazard conditions were represented in the model with the Relevant hazard rating of the day and the Types of avalanche problems present. Since ski runs can cross several elevation bands (e.g., a ski run can start in the alpine, include skiing at treeline and have its pickup location below treeline), multiple avalanche hazard ratings might apply. To circumvent this issue in our analysis, we derived a Relevant hazard rating of the day for each run by taking the highest hazard rating of the elevation bands the run crosses. Types of avalanche problem present was implemented in the model with binary covariates (1: present; 0: absent), one for each of the eight[1] avalanche problems used by NEH. […]

Footnote 1: Please note that NEH only uses eight types of avalanche problems as they do not specify Glide avalanches problems.

17 Data set: Avalanche problem likelihood

Review

[…] Page 8 Line 31 -32: The CMAH specifies "unlikely" as the lowest likelihood term, how were avalanche problems assessed lower than "unlikely"? […]

Response to the review and changes made to the manuscript

Thank you for highlighting this issue. We realize that our description of the avalanche problem cases that were not included in the analysis was not clear in the original version of the manuscript. We considered cases were both the maximum and the typical likelihood of avalanches were both considered to be “unlikely” to be outliers and excluded them from the analysis. We changed the manuscript in the following way:

[…] Because of the small number of cases, we also excluded avalanche problems where both typical and maximum likelihood were assessed ~~lower than~~ as “unlikely”. […]

18 Data set: Exclusion of data point based on avalanche size

Review

[…] Page 8 Line 29 - 31: This sentence is not entirely accurate. Size 1 avalanches are "relatively harmless to people", whereas Size 1.5 avalanches are not specifically defined and are somewhere between Size 1 "relatively harmless to people" and Size 2 "could injure, bury or kill a person". Further, the analysis would likely be more insightful with avalanche problems assessed with Size 1.5 avalanches included. The

avalanche problem "Loose Dry" is often associated with smaller more predictable avalanching and often isn't assigned avalanche sizes larger than 1.5. Saying that, better insights into the "Loose Dry" avalanche problem will not substantially alter the results of the paper, so I leave it to the authors to decide whether to change the analysis. […]

Response to the review and changes made to the manuscript

We rerun the analysis as suggested and revised the content of the results section accordingly. The model calculations are robust, and all parameter estimates only differed in the sub-decimal range.

Page 8, Line 29ff

[…] Since avalanches of Size 1.0 ~~to 1.5~~ are considered relatively harmless to people (McClung and Schaerer, 2006), we only included avalanche problems in our analysis that were characterized with a maximum destructive size of at least Size 1.5. Because of the small number of cases, we also excluded avalanche problems where both typical and maximum likelihood were assessed ~~lower than~~ as"unlikely". […]

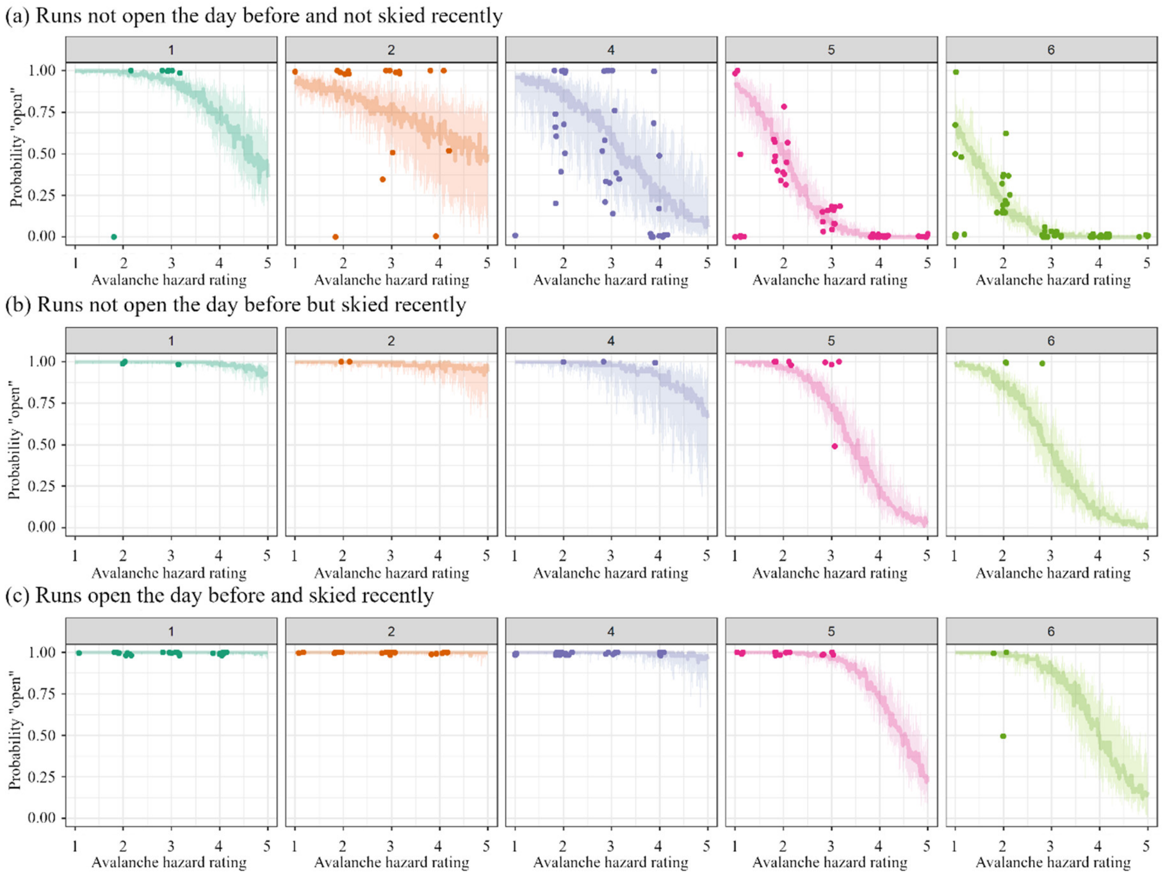
19 Figure 4: Readability, axis label and caption

Review

[…] Page 12 Figure 4: Label the X-axis and increase font size for the axes.
Page 12 Figure 4 caption: Add details that the x-axis represents the relevant avalanche hazard rating. […]

Response to the review and changes made to the manuscript

Thank you for pointing out those graphical flaws. We adapted both the figure and the caption accordingly.



[…] Figure 4: Probabilities of ski runs being open for Storm slab avalanche problems shown for increasing hazard levels with (a) a scenario where ski runs were neither open previously nor skied recently, (b) a scenario where runs were not open the day before but recently skied, and (c) a scenario where runs were open the day before and recently skied. The visualizations include probability intervals of 50% and 95% for each ski run class as a whole based on 50 draws from the posterior distribution. Average daily percentages of open runs per ski run class are plotted as points where observations for this scenario exist in the dataset. […]

20 Figure 5: Observation for run "Shrek"

Review

[…] Page 18 Line 23 - 30: Inspecting Figure 5 for the run "Shrek", I do not observe the negative random intercept: it appears to be non-significant and slightly positive. It does appear to show significant positive OR for Deep Persistent Slabs and Persistent Slabs. Please explain. […]

Response to the review and changes made to the manuscript

Thanks you for pointing out this inconsistency. This was a leftover from a previous draft that we forgot to adjust. We deleted the corresponding part of the results description accordingly.

21 Figure 5: Graphical representation of results

Review

[…] Page 18 Figure 5: -Please increase font sizes as this figure is nearly unreadable. - Change the x-axis

for "Relevant Avalanche Hazard Rating" to match the other formats. - Overall, I might challenge the authors to consider if there would be another graphical format that might convey the key points of this Figure more clearly and concisely. - One of the fascinating results from this plot is the increased variance in OR between avalanche problems, for example the OR for each run under Deep Persistent Slabs and Persistent Slabs show much higher variance compared to the more predictable avalanche problems like Storm Slabs / Dry Loose / Wet Loose. The Relevant Hazard Rating also shows higher relative variance in ORs. - A very insightful set of results that are likely available with this dataset and analysis would be the relative difference of run coding probabilities between avalanche problems with increasing levels of avalanche hazard ratings. i.e., Produce Figure 4 graphs for grouped avalanche problems (Storm and Wind and Loose Dry, Persistent and Deep Persistent, Wet Slab and Wet) or each individual problem, and remove the recency of skiing on the run classification. […]

Response to the review and changes made to the manuscript

Thank you for pointing out this issue and the input into the variance of the by-run random effects for different avalanche problem types. We believe that this angle provides some valuable insight into our results and we therefore made the following changes to the manuscript:

- Presenting the random effects in a new table that shows their variance and lists ski runs with significant random effects as a foundation for the discussion in section "Random effects on run level (currently 3.4). We believe this presentation makes the results more insightful and we omit Figure 5.
- Discussing the overall insight from this with an additional subsection before discussing the effects of run code of the previous day and recent skiing on a run

Table 5: Variance in by-run random effects expressed with the standard deviation per parameter. In addition, ski runs with significant positive or negative random effects are listed. The number in brackets indicate the ski run class.

		Ski runs with significant random effects	
Parameter	***SD***	***Positive random effect***	***Negative random effect***
Intercept	*0.63*	*Poison Beauty (5)*	*Donkey (4), Line King (5)*
Relevant hazard rating	*1.12*	*East Ridge (2), Back Door (5)*	*Pacha Mama (2), Tea Cup (2)*
Deep persistent slab	*0.47*	*Shrek (6)*	*Sea of Cortez (4)*
Persistent slab	*0.23*	*Back Door (5)*	-
Storm slab	*0.06*	-	-
Wind slab	*0.06*	-	-
Cornice	*0.05*	-	-
Loose wet avalanche	*0.12*	-	-
Loose dry avalanche	*0.17*	-	-
Wet slab	*0.31*	-	-

3.3. Overall insight into the effect of avalanche hazard

Together, the main effects, interaction effects by ski run class and by-run random effects provide comprehensive insight into the overall effect of avalanche hazard (i.e., rating and avalanche problem *presence) on run list choices. While a significant main effect indicates that there is a consistent general response to changes in hazard across the entire run list, significant interaction effects mean that specific ski run groups respond differently from the overall pattern described by the main effect. Finally, significant by-run random effects show that individual runs substantially deviate from the general and/or ski run group specific response pattern.*

The results of our analysis reveal that the run list ratings respond to the different aspects of avalanche hazard in different ways. The response to the hazard rating is characterized by a significant main effect (Table 1), significant interaction effects for some of the ski run classes (Table 2), and large variations in the by-run random effects with some of them being significant (Table 5). This means the observed general effect is superimposed with ski run group and ski run specific responses. The different avalanche problem types influence the run list ratings as follows. For Wet slab avalanche problems, only the main effect is significant (Table 1) indicating that all ski run classes respond to this avalanche problem the same way (Table 2). For Deep persistent avalanche problems and Persistent avalanche problems only certain ski run classes respond (i.e., no main effect, but ski run class specific interactions, Table 2), but certain individual ski runs significantly deviate from the overall class pattern with more variation in the by-run random effects (Table 5). For Loose wet avalanche problems, our model shows a non-significant main effect, some significant interactions effects for the different ski run classes and non-significant by-run random effects without any significant variability among runs. Finally, our model indicates no effect at all for Storm slab, Wind slabs, Cornices and Loose dry avalanche problems. This means that the response of the run list to these avalanche problem types is fully captured by the effect of the avalanche hazard rating.

Overall, the observed patterns in run list responses seem to be consistent with the existing understanding of different avalanche problems and the complexity of their management (Wagner and Hardesty, 2014; Haegeli et al., 2010). Since simpler avalanche problem types, such as Storm slab, Wind slab, or Loose dry avalanche problems, are typically widespread and result in relatively short-lived spikes of increased avalanche hazard, the required risk management strategies can be captured by a more general relationship between the avalanche hazard rating and terrain class. On the other hand, because the effects of the more complex Wet slab, Persistent slab and Deep persistent slab avalanche problems can be more localized and/or persist for extended periods, they require more nuanced, avalanche problem specific terrain choices that cannot be explained with the hazard rating alone. This is reflected in the avalanche problem specific fixed and random effects that emerged from our analysis.

References:

Haegeli, P., Atkins, R., and Klassen, K.: Decision making in avalanche terrain - a field book for winter backcountry users. Canadian Avalanche Centre, Revelstoke, BC, Canada, 2010.

Wagner, W. and Hardesty, D: Travel advice for the avalanche problems: A public forecasting tool. In: Proceedings of the International Snow Science Workshop, Banff, AB, Canada, 2014.

22 Technical corrections

Review

[…] Page 3 Figure 1 caption: Delete "Geographical". It is obvious that it is a map.

Response to the review and changes made to the manuscript

We deleted “Geographical” from the sentence.

Review

[…] Page 4 Line 5: Change "(i.e., the run is safe to ski with guests)" to "(i.e., the run is available to guide with guests)".

Response to the review and changes made to the manuscript

This is a valuable comment and we changed the sentence to :

[…] *(i.e., everybody in the guiding team agrees that there is a least one line that can be skied with guests under the current conditions)*. […]

Review

[…] Page 4 Line 15: Delete reference"(Statham et al., 2018)". The CMAH has already been referenced.

Response to the review and changes made to the manuscript

This is a valid comment and we changed the sentence accordingly.

Review

[…] Page 5 Line 21: Reword "at the runs scale".[…]

Response to the review and changes made to the manuscript

Thanks you for pointing this out. We changed the sentence to “at the run scale”.

Review

[…] Page 5 Line 33: Add "(2019)" after Haegeli. […]

Response to the review and changes made to the manuscript

Thank you for pointing this out. We changed the reference accordingly.

[…] Sterchi and Haegeli (2019) first identified groups of ski runs by clustering similarly coded ski runs over the course of several winter seasons. […]

Review

[…] Page 6 Line 1: Change "are" to "were" […]

Response to the review and changes made to the manuscript

Thank you for pointing this out. We changed the sentence accordingly.

Review

[…] Page 6 Line 6: Delete "(Sterchi and Haegeli, 2019)". The study has already been referenced. […]

Response to the review and changes made to the manuscript

We believe the reference should stay to be fully clear to what the description is referring.

Review

[…] Page 6 Figure 2 caption: Please confirm whether the Sterchi and Haegeli study is under review or has been published 2019, then update the manuscript accordingly. […]

Response to the review and changes made to the manuscript

Thank you for pointing this inconsistency out. The sentence will included “(Sterchi and Haegeli, 2019)” as the correct reference.

Review

[…] Page 16 Line 12: Typo: "the" should be "they". […]

Response to the review and changes made to the manuscript

Thank you for pointing this out. We changed the sentence accordingly.

Exploring the relationship between avalanche hazard and ~~large-scale~~run list terrain choices at a helicopter skiing operation~~ – Insight from run list ratings~~

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Correspondence to: Pascal Haegeli (pascal_haegeli@sfu.ca)

Abstract. While guides in mechanized skiing operations use a well-established terrain selection process to limit their exposure to avalanche hazard and keep the residual risk at an acceptable level, the relationship between the open/closed status of runs and environmental factors is complex and has so far only received limited attention from research. Using a large data set of over 25 000 operational run list codes from a mechanized skiing operation, we applied a general linear mixed effects model to explore the relationship between ~~acceptable~~ skiing terrain that is deemed appropriate (i.e., status open) and avalanche hazard conditions. Our results show that the magnitude of the effect of avalanche hazard on run list codes depends on the type of terrain that is being assessed by the guiding team. Ski runs in severe alpine terrain with steep lines through large avalanche slopes are much more susceptible to increases in avalanche hazard than less severe terrain. However, our results also highlight the strong effects of recent skiing on the run coding and thus the importance of prior first-hand experience. Expressing these relationships numerically provides an important step towards the development of meaningful decision aids, which can assist commercial operations to manage their avalanche risk more effectively and efficiently.

1 Introduction

The majestic mountains and abundant powder snow make Western Canada a world renown destination for winter backcountry recreation. One of the key players in ~~winter backcountry recreation in Canada~~this activity is the mechanized skiing industry, where professionally trained guides take paying clients to remote untracked powder slopes using helicopter and snowcats. The industry has been growing since its inception in the 1960s and offers more than 100 000 skier days per winter today (HeliCat Canada, 2016). However, winter backcountry travel is not without risks. Snow avalanches are the most significant hazard affecting daily operations in mechanized skiing in Canada (Bruns, 1996). Walcher et al. (2019) report that between 1997 and 2016, avalanches accounted for 77% of the overall natural hazard mortality in mechanized skiing in Canada. Operations manage the~~is~~ risk from avalanches by continuously assessing the local ~~avalanche~~ hazard conditions and carefully choosing appropriate terrain and travel procedures to limit their exposure ~~to avalanche hazard~~ and keep the residual risk at an acceptable level while still providing a high-quality skiing experience. In addition, some operations use explosives to directly control avalanche hazard or purposely ski individual runs to control future avalanche hazard by modifying the local snowpack (commonly referred to as “run maintenance”).

In Canada, mechanized skiing operations select terrain for skiing by following a well-established, iterative process. This risk management process has been described as a series of filters occurring at multiple spatial and temporal scales (Israelson, 2015) that progressively eliminate skiing terrain from consideration (Figure 1). The daily process starts with a morning meeting where the guiding team assesses the current hazard conditions and produces a first large-scale avalanche hazard forecast across the entire tenure based on the previous day’s experiences and the observed overnight changes. ~~for the day ahead.~~ This initial hazard assessment is the foundation for the day’s “run list”, which represents the first terrain elimination filter. In this step, the guiding team ~~goes through~~discusses their inventory of predefined ski runs and collectively decides for each run whether it is open or closed for ~~skiing~~ guiding with guests under the expected avalanche hazard conditions. It is important to note that depending on the nature of the operation, the scale of ski runs can range from tightly defined ski lines to areas the size of a medium ski resort. However, regardless of their size, the nature of ski run is consistent enough that they represent meaningful decision units at this stage of the risk management process. The large-scale, consensus-based run list that emerges from the morning meeting sets the stage for the skiing program of the day. Over the course of a skiing day, ~~terrain choices are further~~the avalanche hazard assessment is refined ~~and adapted in response to~~based on direct field observations and runs that are skied are chosen from the run list accordingly. In most helicopter skiing operations, helicopters serve multiple groups of skiers, each of them led by a guide. It is common practice that the guide of the first group serviced by the helicopter (known as the ‘lead guide’) decides what runs the groups of this helicopter ski. This run choice represents the second filter in the terrain selection process. The third and final filter of the terrain selection process is the decision of how exactly a particular run is skied, which is the responsibility of the guide of each group. This sequence of (1) run list established by entire guiding team, (2) run choice made by the lead guide and (3) ski line choice within run made by individual guides, highlights the hierarchical and iterative nature of the terrain selection process. At each filter level, the decisions are refined based on avalanche hazard assessments at increasingly smaller scale ~~avalanche hazard assessments~~. While avalanche hazard is a critical factor in this process, other factors such as weather and flying conditions, flight economics, skiing quality, guest preferences and skiing abilities also affect the selection and sequencing of the skied ~~terrain~~ runs (Israelson, 2015). This terrain selection process is repeated every day, and guiding teams continuously adjust their terrain choices in response to the observed changes in avalanche hazard conditions. While the steps of the terrain selection process are well defined and easy to describe, the relationship between environmental factors and terrain selection is complex and has so far only received limited attention from research. Grímsdottír (2004) and Haegeli (2010) identified critical terrain and avalanche hazard factors contributing to the terrain decisions at the run scale but did not examine the relationship between avalanche hazard conditions and run list codings in more detail. While Hendrikx et al. (2016) and Thumlert and Haegeli (2018) studied the association between small-scale terrain choices and avalanche conditions quantitatively by analyzing patterns in GPS tracks, they did not account for the fact that these choices are embedded in the~~a~~ higher-level, hierarchical and continuous terrain selection process described above. Having an in-depth, quantitative understanding of each stage of the terrain selection process is critical for properly tapping into the risk management practices of guiding teams and describing it in a way that offers useful insight into the influencing factors. Only a comprehensive perspective will allow us to capture the existing tacit expertise, isolates the effect of avalanche hazard and extract information on relevant patterns in a way that facilitates learning from the past and developing decision support tools that can aid the terrain selection process ~~in a professional context~~ in ~~a~~ meaningful ways~~. Furthermore, a quantitative understanding of the professional terrain selection process that properly isolates the effect of avalanche hazard can offer the foundation for the development of terrain guidance for recreationists~~.

The objective of our study is to advance our understanding of the professional avalanche risk management process by quantitatively examining the relationship between ~~acceptable~~ appropriate skiing terrain (i.e., open or closed for guiding) and avalanche hazard conditions at the run list scale using ~~historic~~ recorded avalanche hazard assessments and run list ratings from a commercial helicopter skiing operation.

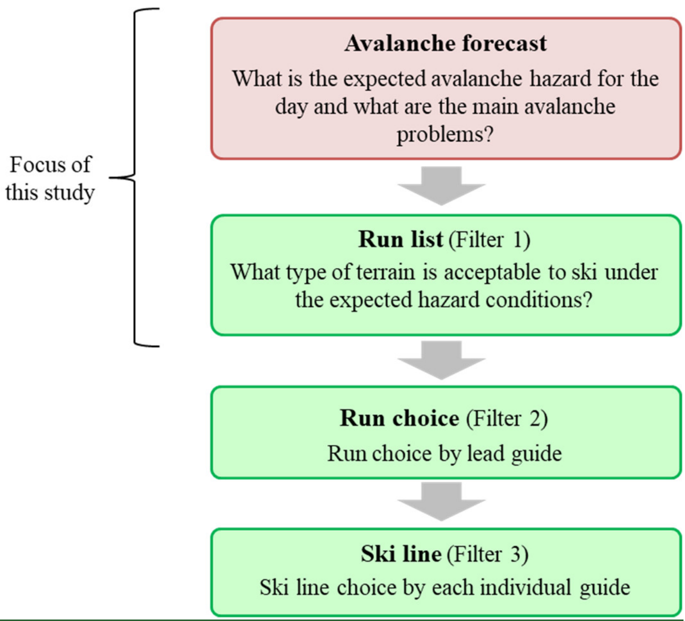


Figure 1: Hierarchical terrain selection process in mechanized skiing in Canada.

2 Methods

2.1 Study site

For this study, we collaborated with Northern Escape Heli Skiing (NEH), a commercial helicopter skiing company based out of Terrace, BC, Canada (Figure 2~~Figure 1~~). NEH's operating tenure is in the Skeena Mountains and spans an area of nearly 6000 km^2. The skiing terrain ranges from 500 m to 2000 m above sea level covering all three elevation bands (alpine, treeline and below treeline). While their entire tenure has 260 established ski runs, much of their skiing is focused on approximately 60 runs in their home drainage, which is the focus of our study. The character of the local snow climate is maritime with storm slab avalanche problems during or immediately following storms being the primary avalanche hazard concerns (McClung and Schaerer, 2006; Shandro and Haegeli, 2018).

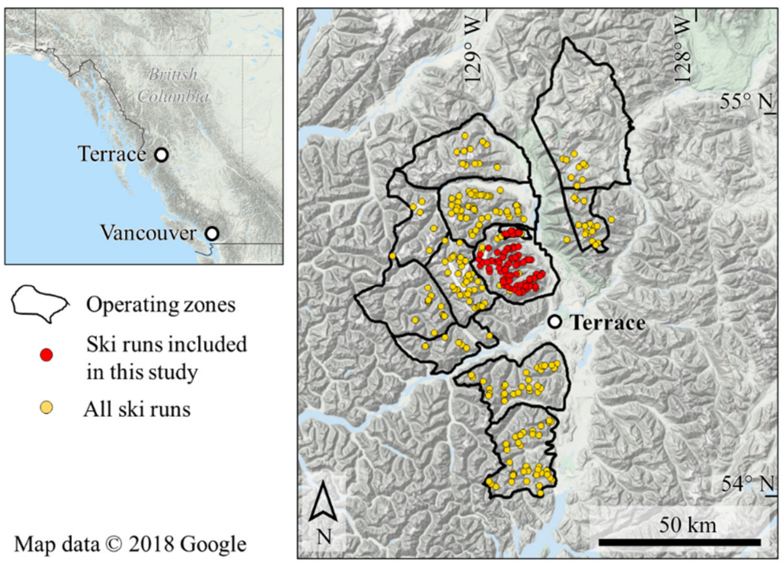


Figure 2~~1~~: ~~Geographical overview~~Overview of the study site with location of the tenure region and the ski runs for one of the operating zones included in this study.

2.2 Data set

The primary dataset used in this study consists of daily run list and avalanche hazard information for the six winter seasons 2012/13 to 2017/18 (517 operational days between December 1 and March 31 of each season). The run list dataset consists of 26 488 individual run ratings in total, one for every run on each of the 517 operational days. At NEH, the guiding team codes runs as either “Open for guiding” (i.e.,~~ the run is safe to ski~~~~available to guide with guests~~ everybody in the guiding team agrees that there is a least one line that can be skied with guests under the current conditions), “Closed for guiding due to avalanche hazard” (i.e., ~~any ~~members of the guiding team ~~is ~~are not comfortable with taking guests onto that run), “Closed for guiding for reasons other than avalanche hazard” (e.g. other mountain hazards such as crevasses, open creeks, ski quality) or “Not discussed” (i.e., ski runs in zones not considered are automatically closed for skiing that day).

NEH’s avalanche hazard assessment process follows the Conceptual Model of Avalanche Hazard (CMAH, Statham et al., 2018), which ~~provides a framework that ~~structures the process around the identification and characterization of avalanche problems. Avalanche problems represent ~~actual ~~operational concerns about potential avalanches that can be described in terms of the type of avalanche problem, the location in the terrain where the problem can be found, the likelihood of associated avalanches, and their destructive size. The concept of avalanche problem type ~~plays a central role in the CMAH as it~~ represents the idea that distinct types of avalanches that emerge from specific snowpack structures and weather events require different risk mitigation approaches ~~(Statham et al., 2018)~~. ~~Overall,~~ Statham et al. (2018) and describe nine distinct types of avalanches problems (*Dry loose avalanche problem*, *Wet loose avalanche problem*, *Storm slab avalanche problem*, *Wind slab avalanche problem*, *Persistent slab avalanche problem*, *Deep persistent slab avalanche problem, Wet slab avalanche problem*, *Glide avalanche problem*, and *Cornice avalanche problem*) that differ in their development, avalanche activity patterns, how they are best recognized and assessed in the field, and what risk management strategies are most effective for managing them. While some avalanche problems are of relatively short duration and can be managed easily by avoiding specific terrain features within runs (e.g., wind-loaded slopes when a wind slab avalanche problem is present), others, such as persistent slab avalanche problem can linger for weeks, even months, and require a more conservative risk management approach that excludes a broader range of terrain (Haegeli et al., 2010; Statham et al., 2018). ~~*Wind slab avalanche problems*, for example, represent cohesive slabs of wind-deposited and broken snow-particles that are typically found on lee-ward (downwind) slopes or in cross-winded areas where winds blow across the terrain. *Wind slab avalanche problems* are relatively easy to manage as the associated avalanches are often limited in size, typically restricted to well-defined terrain features, and tend to stabilize within one or two days after a significant wind event. *Deep persistent slab avalanche problems*, on the other hand, are caused by a thick and hard cohesive slab of snow losing its bond to an underlying weak layer that is deeply buried in the snowpack, often on or near the ground (Haegeli et al., 2010). The formation of *Deep persistent avalanche problems* typically begins in the early season, when conditions are ideal for the development of depth hoar or rain-on-snow events creating facet/crust combinations that are subsequently buried. These weak layers can persist for months and often go dormant with only occasional associated avalanche activity before substantial weather changes in the spring reactivates them again. Since there are often no visible signs of deep persistent slab instability, and associated avalanches tend to be large and essentially not survivable, the management of *Deep persistent slab avalanche problems* is extremely challenging and requires very conservative terrain choices.~~

After the guides at NEH have identified the types of avalanche problems they are concerned about, they describe the terrain they expect to encounter these problems in terms of elevation bands (alpine, treeline and below treeline) and aspect ranges. The likelihood of avalanches ~~includes both~~combines the sensitivity to triggers and the spatial distribution and is expressed on an ordinal scale using the qualitative terms 'unlikely,' 'possible,' 'likely,' 'very likely' and 'almost certain' (Statham et al., 2018). Destructive size is assessed according to the Canadian avalanche size classification (Canadian Avalanche Association, 2014) on a scale ranging from 1.0 (relatively harmless for people) to 5.0 (largest snow avalanche known ~~for a given path~~, ~~which~~ could destroy a village or a large forest area of approximately 40 hectares). Guides express their uncertainty in hazard assessments by specifying ranges of likelihood and size for each avalanche problem (minimum, typical, and maximum for both parameters). The hazard assessments for each elevation band are concluded by summarizing the overall hazard level that emerges from the combined avalanche problems with a single hazard rating on an ordinal scale from 1 (least hazardous) to 5 (most hazardous) (Canadian Avalanche Association, 2015).

To identify meaningful patterns between avalanche hazard and terrain choices numerically, it is critical to encode the nature of the available ski runs in a way that is ~~concise, but~~ insightful~~ way~~, but too complex for the analysis. To comprehensively capture of complex nature of entire ski runs into our model in a way that reflects how professional guides perceive them, we used the approach introduced by Sterchi and Haegeli (2019), which groups the ski runs into operation-specific terrain classes based on multi-seasonal patterns in run list ratings (i.e., revealed terrain preferences). ~~Avalanche terrain research in the context of backcountry recreation has traditionally primarily focused on standard terrain characteristics such as slope incline, slope shape, elevation, aspect, and vegetation density (e.g., Hendrikx et al., 2016; Thumlert and Haegeli, 2018). More recently, Harvey et al. (2018) developed a more sophisticated approach that combines an automated identification of potential avalanche release areas with avalanche simulations using RAMMS::EXTENDED (Bartelt et al., 2012; Bartelt et al., 2016) and fall simulations to develop thematic avalanche terrain maps that identify potential avalanche release areas, remote triggering of avalanches, possible runout zones, and the potential of being seriously injured or deeply buried by small or medium-sized avalanches. While the approach by Harvey et al. (2018) offers a much more comprehensive perspective on the nature of avalanche terrain than individual terrain parameters, the assessment is still at the level of individual raster cells, and it is not completely clear how to combine and summarize these terrain characteristics at the runs scale in a way that fully represents its hazard potential and the overall character of the skiing terrain. Furthermore, in the context of a commercial skiing operation, frequency of use and operational risk management practices (e.g., managing of avalanche hazard through skier compaction or explosive control) also play an important role on whether a particular run is suitable under different hazard conditions, and the overall attractiveness of a run is further determined by potential access barriers, the general nature of the terrain, the quality of the skiing experience, the operational role of the run and its guidability (Wakefield et al., 2018). These aspects are not only determined by the character of ski runs, but also by the nature of the landing and pickup locations of the run, the operational practices at the operation, and the particular skiing product the operation offers to their clients. To overcome this complexity and include the nature of the ski runs into our model in a way that reflects how professional guides perceive them, we employed the ski run classification developed by Sterchi and Haegeli (2019).~~ Sterchi and Haegeli (2019) first identified groups of ski runs by clustering similarly coded ski runs over the course of several winter seasons. Subsequently, they arranged the identified groups into a hierarchy that ranges from runs that are almost always open to runs that are only open when conditions are favourable. To better understand the nature of the revealed ski run classes, the authors had a senior lead guide at each participating operation provide a comprehensive but structured description of their ski runs with respect to access, type of terrain, skiing experience, operational role, hazard potential, and guide-ability. Since this ski run classification is based on past operational risk management decisions, it reflects the local terrain expertise and avalanche risk management practices in the context of the available terrain and local snow and avalanche climate conditions (Sterchi and Haegeli, 2019). .~~In comparison to existing terrain classification systems with small numbers of universal terrain classes (e.g., ATES; Statham et al., 2006; Campbell and Gould, 2013), Sterchi and Haegeli's approach identifies high-resolution, operation-specific ski run hierarchies based on multi-seasonal patterns in run list ratings (i.e., revealed terrain preferences).~~ Thus, this approach represents a more meaningful characterization of ski run classes to analyze professional terrain choices in mechanized skiing operations than existing terrain classification systems which have small numbers of universal terrain classes (Statham et al., 2006; Campbell and Gould, 2013) or focus primarily on standard terrain characteristics such as slope incline, slope shape, elevation, aspect, and vegetation density (e.g., Hendrikx et al., 2016; Thumlert and Haegeli, 2018).

At NEH, the analysis of Sterchi and Haegeli (2019) identified six distinct classes of ski runs. ~~To illustrate the nature of the skiing terrain included in this study,~~ Figure 3~~Figure 2 shows the average seasonal percentage of run code 'open' for each ski run grouped into the six classes and Table 1 provides an overview of the general character of the NEH ski runs.~~ While the severity of terrain generally increases from Class 1 to Class 6, as illustrated by the average seasonal percentage of run code 'open' for each ski run (Figure 3) and the terrain photos of example runs (Table 1), the groupings also reflect other run characteristics like accessibility, quality of skiing experience and operational practices.

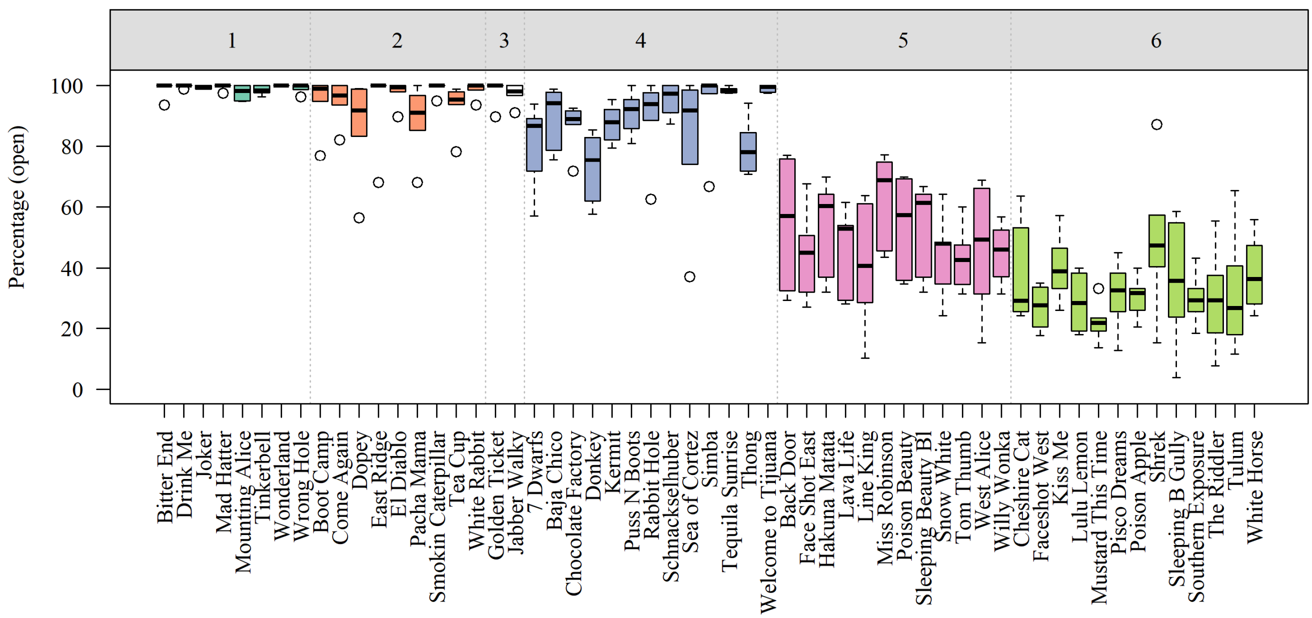
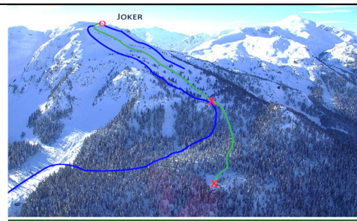
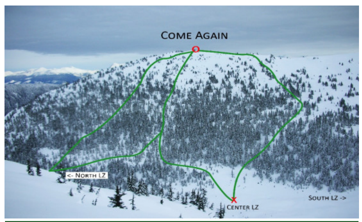
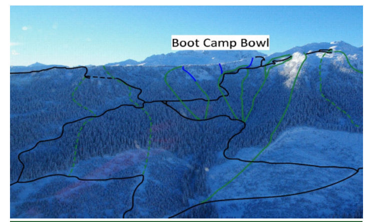
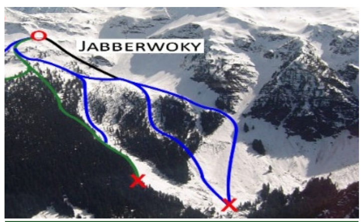
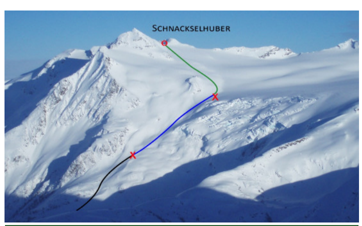
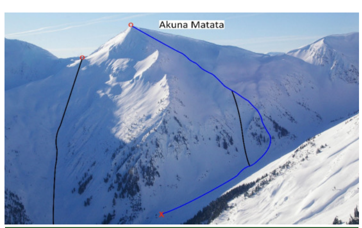
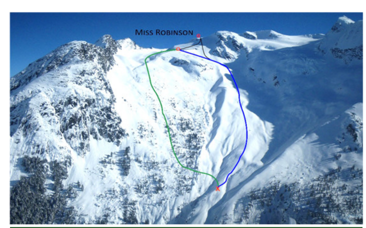
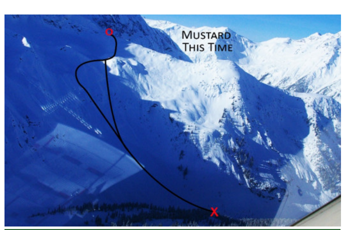
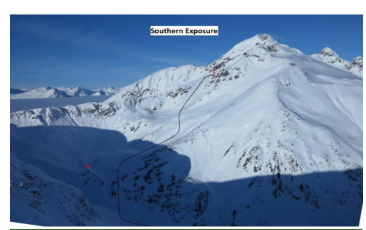


Figure 3~~2~~: Boxplot of a~~A~~verage seasonal percentages of run code 'open' for the 57 ski runs during the six seasons 2012/13 to 2017/18 with the six identified classes of similarly managed ski runs (Sterchi and~~&~~ Haegeli, 2019~~under review~~). Due to the small group size and their outlier characteristics, the two runs of Class 3 were not included in the present analysis.

The first three classes generally consist of easily accessible and mostly gentle ski runs with no or only limited exposure to avalanche slopes. Most of the skiing is through open slopes at tree line, open canopy snow forest below tree line, ~~or~~ non-glaciated or glaciated alpine. The main difference between the first two classes is that the runs of Class 1 provide a better skiing experience. Since Class 1 runs are more attractive, they are typically skied more often, guides have a better handle on the local conditions, and hence the runs are coded open more consistently. The two runs included in Class 3 are of similar general character, but they are located at lower elevations, which makes them more vulnerable to rising freezing levels. Due to the small group size and their outlier characteristics, we excluded them from the present analysis. While most of the ski runs of the first three groups are at tree line and below, Class 4 to 6 predominantly consist of alpine terrain. Class 4 consists of ski runs in gentle alpine terrain or open slopes at tree line where most ski lines do not cross any avalanche slopes. These ski runs are often accessible and provide generally a good skiing experience with easy or moderately challenging skiing. However, some of the ski runs can be exposed to overhead avalanche hazards during regular avalanche cycles. The ski runs included in Class 5 are also located in the alpine but are substantially steeper and cross avalanche slopes more frequently than the runs of Class 4. Furthermore, almost half of the ski runs in Class 5 can be directly affected by overhead hazard during regular avalanches cycles and many pickup locations are threatened by overhead avalanche hazard during large avalanche cycles. While skiing on these runs was characterized as moderately challenging, they offer very good or even “life-changing” skiing experiences for guests. Class 6, the highest group in the NEH ski run hierarchy, mainly consists of runs in the most serious alpine terrain skied at NEH. The runs are rarely skied but can play an important operational role when conditions are appropriate. Most of these runs have moderately steep or steeper slopes that can produce avalanches of Size 3.0 or bigger and many pickup locations are exposed to overhead avalanche hazard during regular avalanche cycles. However, they provide good or very good skiing experiences for the guests.

Table 1: Photos of typical ski runs included in the different ski run classes. All photos reproduced with permission of NEH.

Class	Number of runs	Typical ski runs	
Class 1	8		
Class 2	9		
Class 3	3		
Class 4	13		
Class 5	12		
Class 6	13		

2.3 Statistical analysis

Since our dataset consists of repeated run list codes for the same runs over the course of several winters, traditional regression models that require observations to be independent from each other are inappropriate for our analysis (Long, 2012). Mixed effects models are an extension of traditional regression models that allow for heterogeneity, nested data, temporal or spatial correlation in longitudinal and/or clustered datasets by relaxing some of the necessary assumptions (Bolker et al., 2009; Zuur et al., 2009; Harrison et al., 2018). To overcome the issue of repeated measures and nested data, mixed effects models include both fixed and random effects in the regression equation. The fixed effects, which are equivalent to the intercept and slope estimates in traditional regression models, capture the relationship between the predictor and response variables for the entire dataset. While traditional regression models assign the remaining unexplained variance in the data (i.e., randomness) entirely to the global error term, mixed effect models partition the unexplained variance that originate from groupings within the dataset into random effects. Thus, random effects can highlight how groups within the dataset deviate from the overall pattern described by the fixed effects. Similar to the parameter estimates for fixed effects, random effects can include both intercept and slope parameters. While random intercepts explain how the average conditions within groups deviate from the average conditions across the entire dataset, random slopes capture group-specific differences in the relationship between the predictor and response variables. The overall response of a particular group to the predictor variables can therefore be described as the linear combination of the overall fixed effects and the group-specific random effects.

Since our target variable, the acceptability of a run, is binary (i.e., open or closed), a logistic regression model is most suited for our analysis. In their basic form, logistic regression models use the logistic function to model the relationship between a binary dependent variable and one or more predictors x_i. In such a model, the probability of Run_k being "open" can be expressed with

$$Prob\ (Run_k = "open") = \frac{1}{1+e^{-\left(\beta_0 + \sum_{i=1}^{j} \beta_i \mathrm{f}_i(x_{ik})\right)}}. \tag{1}$$

In this equation, β_0 is the intercept, β_i are the regression parameter estimates associated with the functional forms f_i~~()~~ (e.g., transformations such as coding a categorical variable into dichotomous variables) of the predictors x_i included in the model. The linear combination of the functional form of the predictors x_{ik} multiplied with the parameter estimates β_i in the exponent in the denominator represents the log-odds (the logarithm of the odds) of Run_k being "open". The components of the equation can be interpreted as follows: The intercept β_0 represents the log-odds when all predictors are zero. A parameter estimate of $\beta_i = 1$ or $\beta_i = 2$ means that a one unit increase in $\mathrm{f}_i(x_{ik})$ increases the log-odds of Run_k being open by 1 or 2, respectively. This is referred to as the "effect" of the predictor x_{ik}. The most common way to express the effect of predictors in logistic regression models is odds ratios (OR), which can be derived by applying an exponential function to the regression coefficients. Hence, parameter estimates significantly larger than zero result in OR > 1, which means that the odds of Run_k being open increases relative to the base level, whereas parameter estimates significantly smaller than zero produce OR < 1 that highlight that the odds of Run_k being open decreases.

To examine the acceptability of runs (i.e., being open or closed) under different hazard conditions, we regressed their daily run list codes against the hazard situation with the runs’ terrain characteristics, their past use and their run list codes of the previous day as covariates (Figure 4~~Figure 3~~). To focus our analysis on the effect of avalanche hazard on open and closed status of runs, we simplified the categorical run list ratings before fitting the regression model. Run list codes indicating that a run was open (i.e., “Open for guiding”) were ~~re~~coded ~~to~~ as 1, whereas run list codes indicating that a run was closed because of avalanche concerns (i.e., “Closed for guiding due to avalanche hazard”) were coded as 0. Run list codes indicating that a run was not considered for any other reasons (i.e., “Closed for guiding for reasons other than avalanche hazard”, “Not discussed”) were excluded from the analysis.

Avalanche hazard conditions were represented in the model with the *Relevant hazard rating* of the day and the *Types of avalanche problems* present. Since ski runs can cross several elevation bands (e.g., a ski run can start in the alpine, include skiing at treeline and have its pickup location below treeline), multiple avalanche hazard ratings might apply. To circumvent this issue in our analysis, we derived a *Relevant hazard rating* of the day for each run by taking the highest hazard rating of the elevation bands the run crosse~~d by the run~~s. *Types of avalanche problem present* was implemented in the model ~~as eight~~with binary covariates (1: present; 0: absent), one for each ~~representing one~~ of the eight[1] avalanche problems ~~specified by the CMAH~~used by NEH. Because the avalanche problems are also assessed for each elevation band separately, we derived relevant daily avalanche problem values for each run similarly to the relevant hazard rating described above. Since avalanches of Size 1.0 ~~to 1.5~~ are considered relatively harmless to people (McClung and Schaerer, 2006; Canadian Avalanche Association, 2014), we only included avalanche problems in our analysis that were characterized with a maximum destructive size of at least Size ~~2.0~~1.5. Because of the small number of cases, we also excluded avalanche problems where both typical and maximum ~~the maximum~~ likelihood was assessed ~~lower than~~ as “unlikely”. To allow our model to account for the possibility that the effect of avalanche hazard on the acceptability of a run being open might differ among terrain types, we interacted the *Relevant hazard rating* and all eight binary variables for *Types of avalanche problem present* with *Ski r~~R~~un c~~C~~lass*.

To account for the iterative character of the terrain assessment process in mechanized skiing, we included two variables in our model that represent critical temporal influences on run list codes. *Skied in the previous seven days* represents past use, which offers both first-hand skiing experience and direct weather, snowpack and avalanche observations for a run. *Run code of the previous day* was included to account for the direct influence of previous run lists on subsequent days. To acknowledge possible correlations between *Skied in the previous seven days* and *Run code of the previous day* (i.e., a run needs to be open to be skied) we also added the interaction between these two variables to our model.

[1] Please note that NEH only uses eight types of avalanche problems as they do not specify *Glide avalanches problems*.

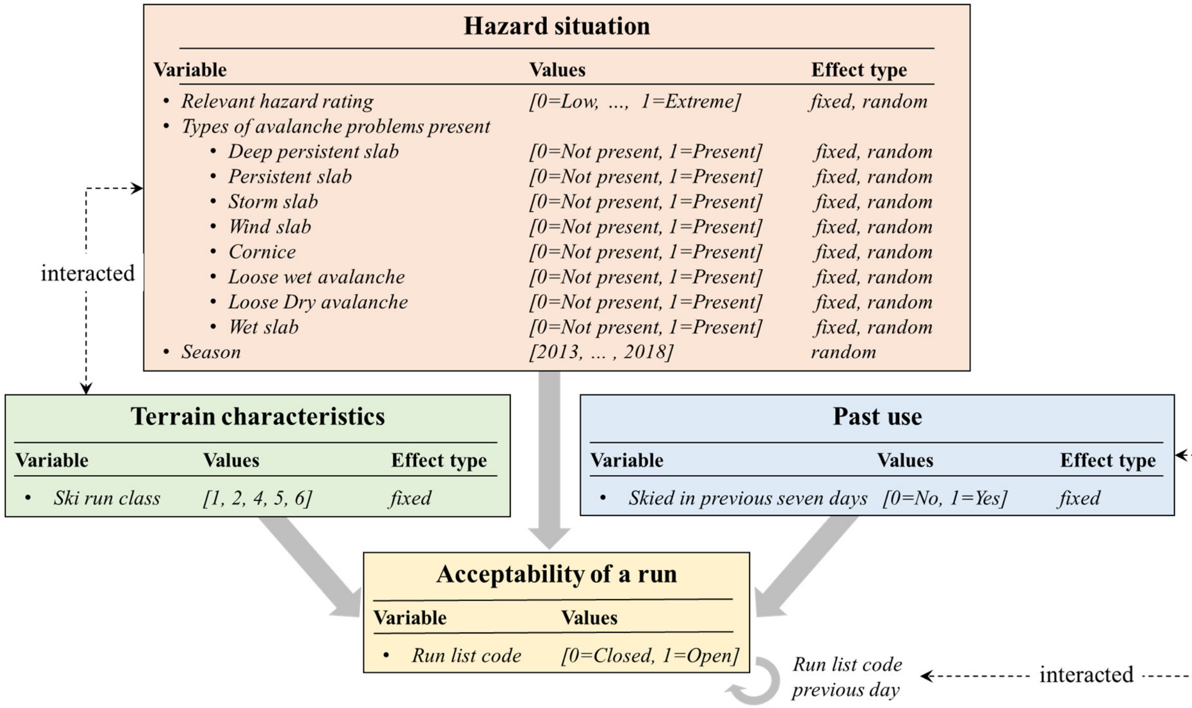


Figure 4~~3~~: Illustration of the model. Our model included variables describing the hazard situation, the terrain characteristics of a ski run, and its past use to examine their relationships with the acceptability of a run (e.g., it being coded "open"). To account for the iterative character of the terrain assessment process~~ in mechanized skiing~~, the model also included the run list code from the previous day. In addition to the fixed effects~~ (FE)~~, we included by-run and by-season random effects~~ (RE)~~.

Since our dataset consists of repeated ratings of the same runs (i.e., panel structure), we included random by-run intercepts and slopes for hazard and avalanche problems. This allows the model to capture the run-specific effect of hazard and avalanche problems that goes beyond the ski run class specific effect. We also included a random by-season intercepts to account for the unique character of each winter in the model.

We performed the model estimation in a Bayesian framework using the statistical software R (R Core Team, 2019) and the package *rstanarm* (Stan Development Team, 2016). We estimated the model with 2500 warmup and 2500 sampling iterations for four separate sampling chains with default priors. Model convergence was inspected based on the potential scale reduction factor (Gelman and Rubin, 1992), which compares the estimated between- and within-chain variances between multiple Markov chains for each model parameter. Large differences between these variances indicate that a model did not converge while values close to 1.0 indicate good convergence. The Markov chains exhibit some degree of autocorrelation, where a lower autocorrelation indicates more independent sampling of the posterior. The approximate number of independent draws with the same accuracy as the sample of correlated draws is referred to as the effective sample size (ESS). We consider an ESS of greater than 1000 as an indication of independent sampling of the posterior.

To eliminate the potentially undesirable impact a variable might have purely due to its scale, all variables included in the analysis were scaled to the interval 0 to 1. Hence, *Relevant hazard rating* was included in the model as a numeric variable scaled to range between 0 and 1. *Ski ~~Run~~ run ~~Class~~ class* was included as a dummy-coded categorical variable with Class 1 as the reference class, whereas all other predictors were represented as binary variables. We explored different model combinations including models where the avalanche problems of concern were included as categorical variables including combinations of different avalanche problems. Only parameter estimates with 95% credible intervals different from 0 were considered significant.

~~Since we included both ski run class-specific intercepts and ski run class-specific slopes for hazard ratings, interpreting the effect of avalanche hazard on run list ratings directly from the parameter estimates is challenging. To present the combined effect of intercept and slope, we calculated OR for each ski run class and hazard rating based on the regression coefficients. We present this effect in two tables showing (a) the odds ratios of ski run classes being open with increasing avalanche hazard relative to themselves at hazard *Level 1* and (b) the odds ratios of ski run classes being open with increasing avalanche hazard relative to ski run Class 1. While the information presented in these two tables are related, they offer slightly different perspectives.~~

~~To further illustrate our results and make their interpretation more tangible, we calculated the probabilities of runs of different ski run classes being open under different hazard conditions and operational situations. We present the following three operational scenarios: (a) ski runs were neither open previously nor skied recently, (b) ski runs were not open the day before but recently skied, and (c) runs were open the day before and recently skied. For each of these scenarios, we plotted the probabilities of ski runs in each ski run class to be open as a function of the hazard rating and included the 50%, 80% and 95% probability intervals based on the averages of 50 draws from the posterior distribution of the individuals runs from each ski run class. Along with the probability curves, average daily percentages of open runs per ski run class are plotted where observations for this scenario existed in the dataset.~~

3 Results and Discussion

The sampling chains of our model converged successfully as indicated by both the potential scale reduction factor (values of 1.0) and for effective sample size (values > 1000) for all parameter estimates. Since the variable *Ski r~~R~~un c~~C~~lass* was dummy coded in our model, the main effects for the variables that were interacted with *Ski r~~R~~un c~~C~~lass* represent the effect for ~~the *Ski Run*~~ *Class 1*~~.~~, the reference class. The effects for the other classes need to be derived by adding the main effect with the ski run class-specific interaction effect.

3.1 Effect of hazard rating and terrain type

The strongly positive main effect intercept indicates that there is a strong base tendency for the runs of Class 1 to be open at hazard Level 1 (parameter estimate=5.48, Table 2~~Table 1~~). The intercept-ski run class interaction effects for all the other classes are significantly negative (parameter estimates=-3.79, -2.40, -3.03 and -4.75 resp., Table 3~~Table 2~~), which means that overall, they are less likely to be open. As expected, the probability of a run being open decreases substantially with increasing hazard for all ~~types of terrain~~ski run classes as illustrated by the negative main effect for hazard rating (parameter estimate=-6.56, Table 2~~Table 1~~).

Table 2~~1~~: Main effects. Diagnostics and posterior summary statistics of the estimated parameters from the mixed-effects logistic regression model. ESS is the effective sample size for each parameter. Significant parameter estimates are indicated in bold. Non~~t-~~significant (ns) ORs are omitted.

Parameter	Value	ESS	Mean	SD	2.5%	97.5%	OR
Intercept	-	1287~~2185~~	**5.48**~~**5.50**~~	0.81~~0.80~~	3.98~~3.97~~	7.11~~7.09~~	**241.02**~~**247.15**~~
Relevant hazard rating	Extreme	1336~~2198~~	**-6.56**~~**-6.59**~~	1.14~~1.12~~	-8.86~~-8.79~~	-4.38~~-4.40~~	**0.001**~~**0.001**~~
Deep persistent slab	Present	2516~~2516~~	0.76~~0.72~~	0.67~~0.69~~	-0.50~~-0.54~~	2.09~~2.12~~	ns~~ns~~
Persistent slab	Present	1993~~2956~~	0.10~~0.1~~	0.44~~0.45~~	-0.75~~-0.77~~	0.96~~0.98~~	ns~~ns~~
Storm slab	Present	1430~~2353~~	0.23~~0.24~~	0.47~~0.45~~	-0.71~~-0.66~~	1.16~~1.13~~	ns~~ns~~
Wind slab	Present	1809~~2558~~	-0.13~~-0.13~~	0.49~~0.49~~	-1.06~~-1.05~~	0.85~~0.84~~	ns~~ns~~
Cornice	Present	2275~~4240~~	1.33~~1.31~~	1.10~~1.06~~	-0.73~~-0.68~~	3.60~~3.47~~	ns~~ns~~
Loose wet avalanche	Present	2296~~3212~~	0.67~~0.66~~	0.86~~0.86~~	-0.92~~-0.94~~	2.44~~2.45~~	ns~~ns~~
Loose dry avalanche	Present	4442~~10000~~	2.33~~1.14~~	1.41~~1.95~~	-0.37~~-4.90~~	5.16~~2.66~~	ns~~ns~~
Wet slab	Present	3503~~4365~~	**-1.63**~~**-1.60**~~	0.65~~0.64~~	-2.85~~-2.82~~	-0.35~~-0.32~~	**0.20**~~**0.21**~~
Run code previous day:	Open	10000~~10000~~	**2.99**~~**2.99**~~	0.06~~0.06~~	2.87~~2.87~~	3.11~~3.11~~	**19.90**~~**19.89**~~
Skied in previous week	Skied	8247~~10000~~	**3.46**~~**3.44**~~	0.42~~0.42~~	2.68~~2.64~~	4.34~~4.29~~	**31.91**~~**31.19**~~

However, the fact that the interaction effects of the different ski run classes (Table 3~~Table 2~~) differ significantly from each other highlights that the magnitude of this effect strongly depends on the type of ~~terrain~~ ski run being assessed by the guiding team. These patterns are also visible in Figure 5~~Figure 4~~, which shows the probabilities of runs of different ski run classes being open during a *Storm slab avalanche problem* ~~for~~ under different hazard ratings and ~~different~~ operational scenarios~~, but all with a *Storm slab avalanche problem* being a concern~~. ~~To further illustrate our results and make their interpretation more tangible, we calculated the probabilities of runs of different ski run classes being open under different hazard conditions and operational situations.~~ We present the following three operational scenarios: (a) ski runs were neither open previously nor skied recently, (b) ski runs were not open the day before but recently skied, and (c) runs were open the day before and recently skied. For each of these scenarios, we plotted the probabilities of ski runs in each ski run class to be open as a function of the hazard rating and included the 50%~~, 80%~~ and 95% probability intervals based on ~~the averages of~~ 50 draws from the posterior distribution of the individuals runs from each ski run class. Along~~Along with the probability curves, average daily percentages of open runs per ski run class are plotted where observations for this scenario existed in the dataset.~~

~~The visualizations include probability intervals of 50 %, 80 % and 95 % for each ski run class as a whole based on 50 draws from the posterior distribution. Average daily percentages of open runs per ski run class are plotted as points where observations for the scenarios exist in the dataset. We can see that the probability of a run being open decreases more substantially with increasing hazard for runs in Class 5 and 6, whereas the modelled probability curves are less steep for Class 1, 2 and 3 (Figure 5Figure 4a).~~

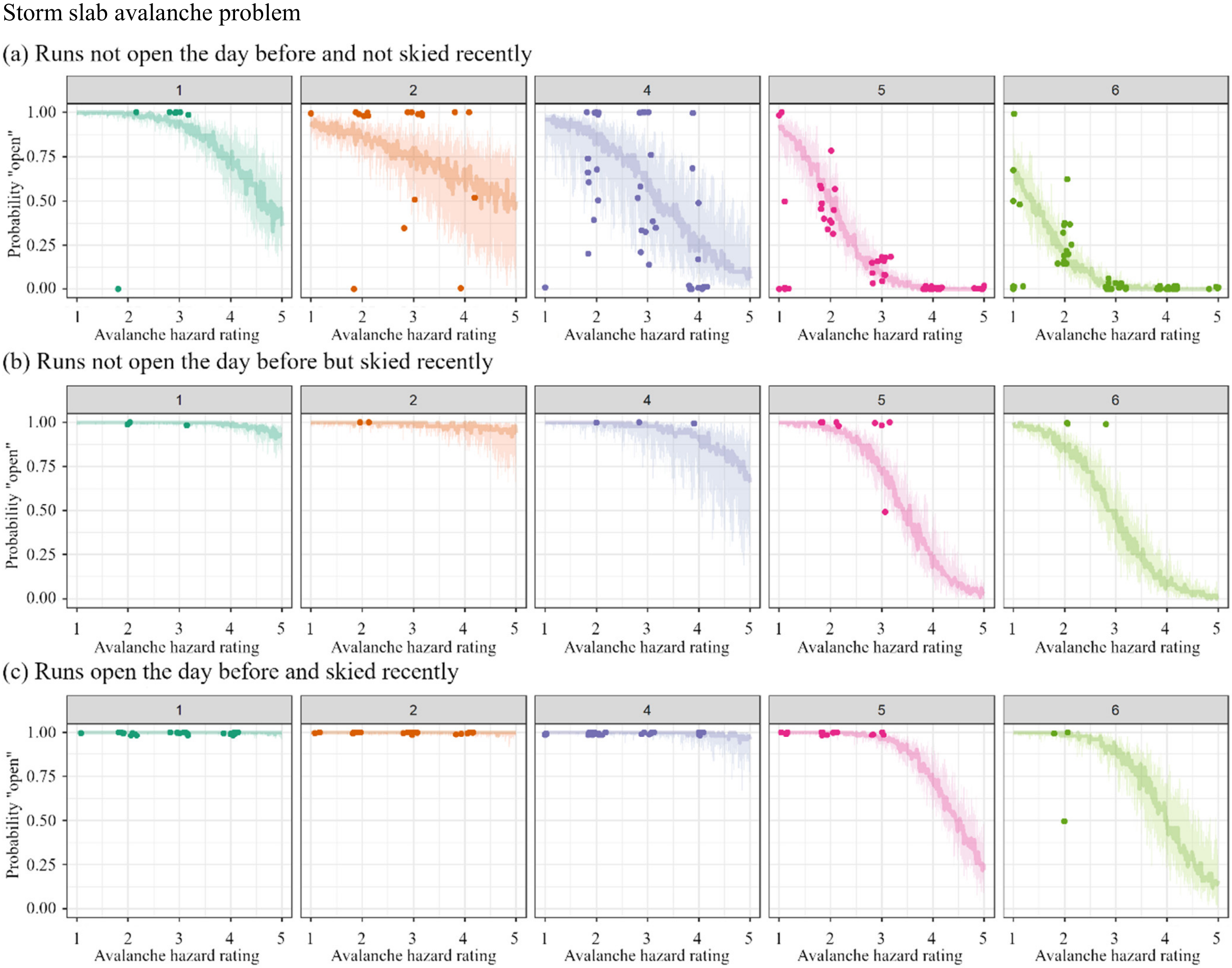


Figure 5~~4~~: Probabilities of ski runs being open for Storm slab avalanche problems shown for increasing hazard levels with (a) a scenario where ski runs were neither open previously nor skied recently, (b) a scenario where runs were not open the day before but recently skied, and (c) a scenario where runs were open the day before and recently skied. The visualizations include probability intervals of 50%~~, 80%~~ and 95% for each ski run class as a whole based on 50 draws from the posterior distribution. Average daily percentages of open runs per ski run class are plotted as points where observations for this scenario exist in the dataset.

with the probability curves, average daily percentages of open runs per ski run class are plotted where observations for this scenario existed in the dataset. The charts show that the probability of a run being open decreases more substantially with increasing hazard for runs in Class 5 and 6, whereas the modelled probability curves are less steep for Class 1, 2 and 3 (Figure 5~~Figure 5~~a).

Table 3~~2~~: Interaction effects. Diagnostics and posterior summary statistics of the estimated parameters from the mixed-effects logistic regression model. ESS is the effective sample size for each parameter. Significant parameter estimates and odds ratios (OR) indicated in bold. Non-significant (ns) ORs are omitted~~Not significant (ns) OR omitted~~.

Parameter	ESS	Mean	SD	2.5%	97.5%	OR
Intercept	-	**-**	-	-	-	**-**
Ski run class 1 (reference level)	-	0.00~~0~~	-	-	-	1.00~~1.00~~
Ski run class 2	1373~~2428~~	**-3.79~~-3.68~~**	0.80~~0.78~~	-5.41~~-5.25~~	-2.30~~-2.17~~	**0.02~~0.03~~**
Ski run class 4	1398~~2440~~	**-2.40~~-2.46~~**	0.79~~0.78~~	-4.00~~-4.00~~	-0.91~~-0.96~~	**0.09~~0.09~~**
Ski run class 5	1315~~2434~~	**-3.03~~-3.13~~**	0.78~~0.76~~	-4.61~~-4.64~~	-1.54~~-1.68~~	**0.05~~0.04~~**
Ski run class 6	1245~~2363~~	**-4.75~~-4.70~~**	0.78~~0.75~~	-6.34~~-6.18~~	-3.30~~-3.25~~	**0.01~~0.01~~**
Relevant hazard rating	-	**-**	-	-	-	**-**
Ski run class 1 (reference level)	-	0.00~~0~~	-	-	-	1.00~~1.00~~
Ski run class 2	1515~~2475~~	**3.46~~3.57~~**	1.30~~1.28~~	0.99~~1.09~~	6.09~~6.07~~	**31.69~~35.52~~**
Ski run class 4	1470~~2336~~	0.69~~0.74~~	1.23~~1.22~~	-1.67~~-1.60~~	3.14~~3.12~~	ns~~ns~~
Ski run class 5	1446~~2368~~	**-3.06~~-3.07~~**	1.25~~1.22~~	-5.51~~-5.46~~	-0.61~~-0.66~~	**0.05~~0.05~~**
Ski run class 6	1393~~2435~~	-2.33~~-2.24~~	1.26~~1.25~~	-4.75~~-4.71~~	0.20~~0.15~~	ns~~ns~~
Deep persistent slab	-	**-**	-	-	-	**-**
Ski run class 1 (reference level)	-	0.00~~0~~	-	-	-	1.00~~1.00~~
Ski run class 2	3200~~3711~~	0.53~~0.60~~	0.80~~0.82~~	-1.04~~-1.06~~	2.10~~2.18~~	ns~~ns~~
Ski run class 4	2609~~2541~~	-0.72~~-0.69~~	0.71~~0.73~~	-2.14~~-2.18~~	0.66~~0.69~~	ns~~ns~~
Ski run class 5	2768~~2805~~	**-2.33~~-2.33~~**	0.73~~0.75~~	-3.81~~-3.86~~	-0.94~~-0.94~~	**0.10~~0.10~~**
Ski run class 6	2870~~3508~~	**-2.59~~-2.66~~**	0.79~~0.82~~	-4.19~~-4.33~~	-1.09~~-1.17~~	**0.07~~0.07~~**

Persistent slab						
Ski run class 1 (reference level)	-	0.00~~0~~	-	-	-	1.00~~1.00~~
Ski run class 2	2374~~3283~~	0.45~~0.36~~	0.51~~0.52~~	-0.56~~-0.64~~	1.44~~1.37~~	ns~~ns~~
Ski run class 4	2066~~3111~~	-0.45~~-0.43~~	0.46~~0.48~~	-1.38~~-1.38~~	0.45~~0.5~~	ns~~ns~~
Ski run class 5	2083~~3035~~	-0.83~~-0.82~~	0.47~~0.47~~	-1.76~~-1.74~~	0.08~~0.09~~	ns~~ns~~
Ski run class 6	2136~~3106~~	**-0.94**~~**-1.19**~~	0.47~~0.48~~	-1.86~~-2.15~~	-0.01~~-0.26~~	**0.39**~~**0.30**~~
Storm slab						
Ski run class 1 (reference level)	-	0.00~~0~~	-	-	-	1.00~~1.00~~
Ski run class 2	1754~~2954~~	0.56~~0.38~~	0.53~~0.52~~	-0.48~~-0.64~~	1.58~~1.39~~	ns~~ns~~
Ski run class 4	1501~~2533~~	-0.26~~-0.25~~	0.49~~0.47~~	-1.23~~-1.19~~	0.70~~0.69~~	ns~~ns~~
Ski run class 5	1520~~2453~~	-0.49~~-0.44~~	0.49~~0.47~~	-1.46~~-1.37~~	0.48~~0.5~~	ns~~ns~~
Ski run class 6	1498~~2504~~	-0.39~~-0.56~~	0.49~~0.47~~	-1.36~~-1.5~~	0.59~~0.36~~	ns~~ns~~
Wind slab						
Ski run class 1 (reference level)	-	0.00~~0~~	-	-	-	1.00~~1.00~~
Ski run class 2	2080~~3026~~	0.45~~0.25~~	0.56~~0.56~~	-0.66~~-0.86~~	1.53~~1.35~~	ns~~ns~~
Ski run class 4	1873~~2708~~	0.14~~0.17~~	0.52~~0.52~~	-0.87~~-0.84~~	1.13~~1.20~~	ns~~ns~~
Ski run class 5	1860~~2676~~	0.21~~0.41~~	0.51~~0.51~~	-0.82~~-0.58~~	1.18~~1.39~~	ns~~ns~~
Ski run class 6	1924~~2637~~	0.31~~0.4~~	0.51~~0.51~~	-0.73~~-0.6~~	1.30~~1.38~~	ns~~ns~~
Cornice						
Ski run class 1 (reference level)	-	0.00~~0~~	-	-	-	1.00~~1.00~~
Ski run class 2	6961~~10000~~	2.00~~1.99~~	1.78~~1.77~~	-1.15~~-1.2~~	5.82~~5.77~~	ns~~ns~~
Ski run class 4	2473~~4411~~	-0.55~~-0.51~~	1.17~~1.12~~	-2.90~~-2.76~~	1.67~~1.65~~	ns~~ns~~
Ski run class 5	2314~~4320~~	-1.12~~-1.09~~	1.12~~1.08~~	-3.42~~-3.26~~	0.98~~0.97~~	ns~~ns~~
Ski run class 6	2317~~4249~~	-0.04~~-0.09~~	1.12~~1.07~~	-2.32~~-2.26~~	2.05~~1.94~~	ns~~ns~~
Loose wet avalanches						
Ski run class 1 (reference level)	-	0.00~~0~~	-	-	-	1.00~~1.00~~
Ski run class 2	2496~~3507~~	-0.79~~-0.94~~	0.92~~0.92~~	-2.66~~-2.81~~	0.96~~0.82~~	ns~~ns~~
Ski run class 4	2628~~3519~~	-0.77~~-0.54~~	0.93~~0.94~~	-2.65~~-2.43~~	1.00~~1.24~~	ns~~ns~~
Ski run class 5	2474~~3345~~	**-1.88**~~**-1.77**~~	0.91~~0.90~~	-3.76~~-3.61~~	-0.18~~-0.08~~	**0.15**~~**0.17**~~
Ski run class 6	2514~~3471~~	-1.25~~-1.31~~	0.93~~0.93~~	-3.12~~-3.21~~	0.47~~0.43~~	ns~~ns~~

Table 2: Continued.

Parameter	ESS	Mean	SD	2.5%	97.5%	OR
Loose dry avalanches						
Ski run class 1 (reference level)	-	- 0.00~~0~~	-	-	-	~~-~~ 1.00~~1.00~~
Ski run class 2	- 10000~~10000~~	0.80~~0.83~~	- 2.14~~2.20~~	- -3.17~~-3.32~~	- 5.33~~5.20~~	ns~~ns~~
Ski run class 4	6207~~10000~~	-1.61~~-2.00~~	1.65~~2.10~~	-4.75~~-6.18~~	1.68~~2.14~~	ns~~ns~~
*Ski run class 5**	8761~~-~~	1.41~~-~~	1.96~~-~~	-2.18~~-~~	5.47~~-~~	ns
*Ski run class 6**	5103~~-~~	1.67~~-~~	1.57~~-~~	-1.42~~-~~	4.80~~-~~	ns
Wet slab						
Ski run class 1 (reference level)	-	- 0.00~~0~~	-	-	-	~~-~~ 1.00~~1.00~~
Ski run class 2	- 4044~~5640~~	0.33~~0.26~~	- 0.81~~0.80~~	- -1.25~~-1.32~~	- 1.89~~1.81~~	ns~~ns~~
Ski run class 4	4166~~5361~~	1.48~~1.46~~	0.79~~0.79~~	-0.05~~-0.10~~	3.03~~2.99~~	ns~~ns~~
Ski run class 5	6177~~10000~~	0.90~~0.96~~	1.10~~1.10~~	-1.41~~-1.28~~	2.92~~3.02~~	ns~~ns~~
Ski run class 6	10000~~10000~~	-0.96~~-0.93~~	1.98~~2.00~~	-5.24~~-5.21~~	2.47~~2.55~~	ns~~ns~~
Run code previous day						
Not skied in previous week (reference level)	-	- 0.00~~0~~	-	-	-	~~-~~ 1.00~~1.00~~
Skied in previous week	- 7647~~10000~~	-0.40~~-0.37~~	- 0.68~~0.68~~	- -1.68~~-1.67~~	- 1.02~~1.04~~	ns~~ns~~

~~* There are no cases in the dataset, where Loose Dry Avalanche Problems were specified for ski runs in classes 5 or 6.~~

Since our model included both ski run class-specific intercepts and ski run class-specific slopes for hazard ratings, interpreting the effect of avalanche hazard on run list ratings directly from the parameter estimates is challenging. To present the combined effect of intercept and slope, we calculated OR for each ski run class and hazard rating based on the regression coefficients. Table 4 shows the odds ratios of ski run classes being open with increasing avalanche hazard relative to themselves at hazard *Level 1.*

~~Combining the group-specific intercept, which represents the base tendency of each group to be open, and the group-specific slope estimate, which shows how strongly the run list codings of a group of runs are affected by increasing hazard, provides a more comprehensive picture. While the odds of runs being open decrease with increasing avalanche hazard ratings in all ski runs classes, the magnitude of the decrease varies substantially (~~Table 4~~Table 3).~~

Table 4~~3~~: Odds ratios of each ski run class~~es~~ being open with increasing avalanche hazard relative to Low avalanche hazard.

	Ski run class				
Hazard	**Class 1**	**Class 2**	**Class 4**	**Class 5**	**Class 6**
Low	1.000~~1.000~~	1.000~~1.000~~	1.000~~1.000~~	1.000~~1.000~~	1.000~~1.000~~
Moderate	0.194~~0.020~~	0.460~~0.049~~	0.230~~0.024~~	0.090~~0.009~~	0.108~~0.011~~
Considerable	0.038~~0.010~~	0.212~~0.059~~	0.053~~0.014~~	0.008~~0.002~~	0.012~~0.003~~
High	0.007~~0.005~~	0.097~~0.072~~	0.012~~0.009~~	0.001~~<0.001~~	0.001~~0.001~~
Extreme	0.001~~0.001~~	0.045~~0.049~~	0.003~~0.003~~	<0.001	<0.001

While the odds of runs being open decrease with increasing avalanche hazard ratings in all ski runs classes, the magnitude of the decrease varies substantially. The odds of the ski runs in Class 1 being open decreases by 1000 times as avalanche hazard goes from *Low* to *Extreme*. In comparison, the ski runs in Class 2 are only about 20 times less likely to be open with the same increase in avalanche hazard. This means that despite the lower overall tendency of runs included in this class to be open, the run list ratings of the Class 2 runs are less affected by danger ratings. Since many of these ski runs are located at or below tree line, we suspect that the observed pattern reflects that many of these runs offer safe skiing options through trees, even when avalanche hazard is elevated. The alpine terrain classes are much more strongly affected by changes in danger ratings as evident by the large negative slope estimates. The odds of the ski runs in Class 4 being open decrease by 300 times with increasing hazard from *Low* to *Extreme*. The odds of the ski runs in Classes 5 and 6 being open decrease even by more than 1000 times. These alpine ski runs are substantially steeper. Moreover, many of the ski runs or pickup locations can be affected by overhead hazard.

Table 5 shows the odds ratios of ski run classes being open with increasing avalanche hazard relative to ski run Class 1. While the information presented in this table is based on the same information as Table 4, it offers a different perspective by ~~Examining the odds of runs in a specific class being open at a specific avalanche hazard relative to Class 1 (~~Table 5~~Table 4)~~ highlighting~~s~~ the relative importance of the various ski run classes at different hazard ratings. For instance, the odds of the runs in Class 2 being open relative to Class 1 increases with increasing avalanche hazard rating. This pattern emerges from the fact that the odds of being open decrease more quickly in Class 1 than in Class 2 (Table 5~~Table 4~~). A similar pattern can be observed between ski run Classes 4 and 5. The ski r~~R~~uns of Class 4 are approximately 10 times less likely to be open at *Low* hazard conditions than ski runs of Class 1. Similarly, the ski runs in Class 5 are approximately 20 times less likely to be open at *Low* hazard conditions than Class 1. However, the ski runs of Class 5 are closed much more quickly as avalanche increases. The relative odds for the ski runs in Class 4 being open are more than 5 times smaller for *Extreme* avalanche hazard, the relative odds for ski runs in Class 5 are 500 times smaller. The s~~S~~ki runs in Class 6 are more than 100 times less likely to be open with *Low* hazard and 1000 times with *Extreme* avalanche hazard than the ski runs in Class 1.

Table 5~~4~~: Odds ratios of each ski run class~~es~~ being open with increasing avalanche hazard relative to ski run class 1.

	Ski run class				
Hazard	**Class 1**	**Class 2**	**Class 4**	**Class 5**	**Class 6**
Low	1.000~~1.000~~	0.023~~0.025~~	0.091~~0.085~~	0.049~~0.044~~	0.009~~0.009~~
Moderate	1.000~~1.000~~	0.054~~0.062~~	0.108~~0.103~~	0.023~~0.020~~	0.005~~0.005~~
Considerable	1.000~~1.000~~	0.128~~0.150~~	0.128~~0.124~~	0.011~~0.009~~	0.003~~0.003~~
High	1.000~~1.000~~	0.303~~0.367~~	0.152~~0.149~~	0.005~~0.004~~	0.002~~0.002~~
Extreme	1.000~~1.000~~	0.719~~0.896~~	0.181~~0.179~~	0.002~~0.002~~	0.001~~0.001~~

As expected, our results confirm that the appropriateness of runs for guiding decreases with increasing hazard. However, they also highlight that the effect of avalanche hazard on run list codes depends heavily on the type of terrain that is being assessed. Gentle and frequently skied terrain in all elevation bands with no or only minor exposure to avalanches slopes is much less affected by avalanche hazard. Severe alpine terrain with exposure to either multiple smaller or even large avalanche slopes on the ski runs or exposure to overhead hazard is much more affected by an increase in avalanche hazard. It is important to note that overhead hazard is not only relevant when it affects a skiing line, but also when the associated pickup locations are threatened.

3.2 Effect of avalanche problems and terrain type

Our results show that only certain avalanche problem types influence run list codes and that their effects differ~~s~~ among ski run classes. The presence of *Deep persistent slab avalanche problems* exhibits a negative effect on the ski runs in Classes 5 and 6. This means that runs in severe alpine terrain are much less likely to be open during times when *Deep persistent slab avalanche problems* are a concern (OR=0.10 and OR=0.07, respectively, Table 3~~Table 1~~). A similar trend emerged for *Persistent slab* *avalanche problems*, but only for the ski runs of Class 6, which showed a significant decrease in the likelihood of being open (OR=0.30). The presence of *Wet slab avalanche problems*, however, exhibited a negative effect on the likelihood of runs being open ~~on~~ for all ski run classes (main effect OR=0.21, Table 2~~Table 1~~). Finally, we observed a negative effect of *Wet loose avalanche problems* on the ~~severe~~ ski runs in Class 5 (OR=0.17).

Compared to the effect of avalanche hazard ratings, the influence of different avalanche problem types is considerably smaller as indicated by the smaller parameter estimates. While hazard ratings reflect the severity of the avalanche hazard conditions in general and affect run codings more globally, avalanche problem types modulate this effect for the specific avalanche situation. For instance, whereas the presence of a widespread *Storm slab avalanche problem* affects the likelihood of ski runs being open equally across all ski run classes, the presence of a *Deep persistent slab avalanche problem* results in a higher likelihood of ski runs with severe alpine terrain with generally steeper or larger avalanche slopes being closed. Similarly, our results only show a significant effect of *Wet loose avalanche problems* on run list coding of severe alpine terrain. While these avalanches are typically confined to surface layers and therefore often small, they can gain size and speed. As such, terrain with severe consequences (e.g., somebody caught in an avalanche being carried into obstacles or over cliffs) seems to be assessed more cautiously.

3.3 Random effects on run level

~~While random effects on the run level were highly significant in preliminary models that did not include ski run class as a covariate, they were mostly insignificant for most ski runs in our final model that included ski run class as covariate (Figure 5Table 6).~~ The insignificance of the run-level random effects of most ski runs (Table 6)~~This~~ highlights that the ski run classes derived by Sterchi and Haegeli (2019) are able to capture the essence of the ski runs, and the realism of the results confirm the suitability of their ski run characterization approach for analysing professional terrain choices in avalanche terrain in a quantitative way.

However, the observed significant random effects ~~still~~ provide useful insight into factors affecting run list choices of individual ski runs that are not captured by the fixed effects included in the model. S~~Some s~~ki runs that exhibit a significant negative random effect are closed more quickly with respect to the particular hazard (i.e., are more sensitive), whereas runs with a significant positive random effect are close less quickly (i.e., are less sensitive) ~~are significantly less sensitive to avalanche hazard (shown in red, Figure 5(Table 6), while others are coded significantly more sensitively with respect to an increase in avalanche hazard (shown in blue, Figure 5~~(Table 6). The run “Sea of Cortez” ~~(Class 4)~~, for example, is significantly less open than the rest of the ski runs of Class 4~~this group of ski runs~~ when *Deep persistent slab avalanche problems* are of concern. We suspect that this difference might be caused by the fact that a more severely exposed line of this ski run can be affected by large overhead avalanche hazard. Similarly, the ski run “Pacha Mama” (Class 2) is significantly less open under conditions with higher hazard than the rest of ~~the group~~its class. While the least severe ski line ~~at treeline~~ on this run only has minor exposure to avalanche hazard, the more severe sections ~~of the run~~ are also exposed to overhead hazard. Both of ~~In both cases, we suspect that such a configuration might also affect the decision to close run sections that have no exposure to avalanche~~

~~hazard. The ski run "Shrek" (Class 6) exhibits another interesting pattern. While it has a negative random intercept indicating that it is significantly less open than the rest of its class, it is significantly more open when *Deep persistent slab* or *Persistent slab avalanche problems* are a concern, or with increased avalanche hazard. A detailed look at the characteristics of "Shrek" provides some insight into the reason behind this pattern. "Shrek" offers moderately steep skiing through glades and snow forest with an open canopy. While skiers are only exposed to smaller avalanche slopes, the run contains tree well hazard and was characterized as unfriendly and not preferred by the guiding team. Based on this characterization, we suspect that "Shrek" is a unfavoured run that is generally closed but potentially opened when operationally needed (i.e., when challenging hazard conditions restrict other skiing options).~~

~~T~~these examples highlight that certain individual attributes of ski runs can be responsible for significant deviations from the typical assessment of ski runs of similar terrain type.

Table 6: Variance of by-run random effects expressed as standard deviations. In addition, ski runs with significant positive or negative random effects are listed. The number in brackets indicate the ski run class.

		Ski runs with significant random effects	
Parameter	**SD**	**Positive random effect**	**Negative random effect**
Intercept	0.63	Poison Beauty (5)	Donkey (4), Line King (5)
Relevant hazard rating	1.12	East Ridge (2), Back Door (5)	Pacha Mama (2), Tea Cup (2)
Deep persistent slab	0.47	Shrek (6)	Sea of Cortez (4)
Persistent slab	0.23	Back Door (5)	-
Storm slab	0.06	-	-
Wind slab	0.06	-	-
Cornice	0.05	-	-
Loose wet avalanche	0.12	-	-
Loose dry avalanche	0.17	-	-
Wet slab	0.31	-	-

3.4 Overall insight into the effect of avalanche hazard

Together, the main effects, interaction effects by ski run class and by-run random effects provide comprehensive insight into the overall effect of avalanche hazard (i.e., rating and avalanche problem presence) on run list choices. While a significant main effect indicates a consistent general response to changes in hazard across the entire run list, significant interaction effects show that specific ski run groups respond differently from the overall pattern described by the main effect. Finally, significant by-run random effects highlight individual runs that deviate substantially from the general and/or ski run group specific response pattern.

The results of our analysis reveal that the run list ratings respond to the hazard rating and the presence of avalanche problems in different ways. The response to the hazard rating is characterized by a significant main effect (Table 2), significant interaction effects for some of the ski run classes (Table 3), and large variations in the by-run random effects with some of them being significant (Table 6). This means the observed general effect is superimposed with ski run group and ski run specific responses. The different avalanche problem types influence the run list ratings as follows. For *Wet slab avalanche problems*, only the main effect is significant (Table 2) indicating that the run list ratings of all ski run classes respond to this avalanche problem the same way (Table 3). For *Deep persistent avalanche problems* and *Persistent slab avalanche problems* only certain ski run classes respond (i.e., no main effect, but ski run class specific interactions, Table 3), and certain individual ski runs significantly deviate from the overall class pattern as indicated by the by-run random effects (Table 6). For *Loose wet avalanche problems*, our model shows a non-significant main effect, some significant interactions effects for the different ski run classes and non-significant by-run random effects without any significant variability among runs. Finally, our model indicates no effect at all for *Storm slab*, *Wind slab*, *Cornice* and *Loose dry avalanche problems*. This means that the response of the run list ratings to these avalanche problem types is fully captured by the effect of the hazard rating.

Overall, the observed patterns in run list responses seem to be consistent with the existing understanding of different avalanche problems and the complexity of their management (Haegeli et al., 2010; Wagner and Hardesty, 2014). Since simpler avalanche problem types, such as *Storm slab*, *Wind slab*, or *Loose dry avalanche problems*, are typically widespread and result in relatively short-lived spikes of increased avalanche hazard, the required risk management strategies can be captured by a more general relationship between the avalanche hazard rating and terrain class. On the other hand, because the effects of the more complex *Wet slab*, *Persistent slab* and *Deep persistent slab avalanche problems* can be more localized and/or persist for extended periods, they require more nuanced, avalanche problem specific terrain choices that cannot be explained with the hazard rating alone. This is reflected in the avalanche problem specific fixed and random effects that emerged from our analysis.

~~3.4~~3.5 Effect of run code of the previous day and recent skiing on a run

Whether a run was open the previous day and whether it was skied within the previous seven days have both a significant influence on it being open ~~on any given day~~ (Table 2~~Table 1~~). ~~Compared~~ Whereas ~~to a run that had neither~~ the effect of a run ~~been skied during the previous seven days not was it open the day before,~~ being open the day before increases ~~a run's~~its odds of being open by 20 times, t~~. T~~he effect of having recently skied the run is even larger, as it increases the odds of a run that was closed the day before to be open by 31 times (Table 2~~Table 1~~). This can also be seen from the modelled probability curves for different hazard levels and operational scenario in Figure 5~~Figure 4~~. Panel (b) illustrates the model results for a scenario where runs were not open the day before but recently skied, whereas ~~and~~ panel (c) shows a scenario where runs were open the day before and recently skied. In both cases, the curves are shifted to the right compared to the base scenario where runs were neither open the day before nor recently skied. ~~We were somewhat surprised, however, by the fact that the interaction between these two parameters did not turn out to be significant.~~

Our results illustrate the strong effect of the run list from the previous day as terrain choices evolve over the course of a season. Terrain choices in mechanized skiing operations are made in stages and are constantly adjusted based on the conditions on the day before incorporating the incremental daily changes (Israelson, 2015). Moreover, the strong effect of previous skiing supports the often-expressed importance by guides of experiencing the conditions and having recent first-hand field observations. This effect is even more important than being open the previous day. As the season progresses, runs that have been skied before and where the guiding team has recent observations about the specific conditions on that run are opened more quickly than comparable runs where such recent experiences are lacking. Previous skiing is an important part of managing risk in heli-skiing as it is considered as a compaction and stabilization factor (Clair Israelson, personal communication, 2019). While these results nicely reflect known guiding practices, we were somewhat surprised that the interaction between these two parameters did not turn out to be significant.

Together, these ~~effects~~results underline the necessity for analysing professional terrain choices in their temporal context. While revealed terrain preference data from GPS tracking units (e.g., Hendrikx et al., 2016; Thumlert and Haegeli, 2018) offer promising avenues for learning about professional avalanche risk management expertise at spatial scales below the run level, it is important to remember that these terrain decisions cannot be analysed as independent, isolated samples as they are always made in an operational context. It is therefore imperative to analyse the observations in the proper temporal context (i.e., open previously, skied previously) and spatial context (run list codes, run use, skied line on a run) to extract meaningful relationships between hazard and terrain choices that can be generalized.

~~3.5~~3.6 Seasonal differences

~~We included a second random effect in the analysis to account for the particularities of individual seasons.~~ The ~~resulting~~ random intercepts for season (Figure 6~~Figure 6~~) reflect differences in the general propensity of runs being open in each season ~~(Figure 6Figure 6)~~. Our results show that runs were coded open less than half as often during ~~the low snowpack winter of~~ 2014 winter season compared to other seasons (OR = 0.3). Overall, winter 2014 was characterized by record low snowpack heights which especially affected the closure of low elevation ski runs due to the marginal snowpack or increased skiing hazards for the guests. In addition, a persistent weak layer that was buried mid-season and remained a concern for the remainder of the season was responsible for the more frequent closures~~e~~ of the more severe ski runs.

This result highlights that having long-term datasets is critical for identifying meaningful patterns in risk management practices as the unique characteristics of individual winters can affect observed choices considerably. Since we are interested in extracting generalizable terrain choice rules, it is important to work with ~~a~~ statistical methods that ~~is able to~~can account for such random deviations. Hence, mixed effects models are an excellent approach for analysing terrain choices as they properly account for the nested structure of terrain selection datasets.

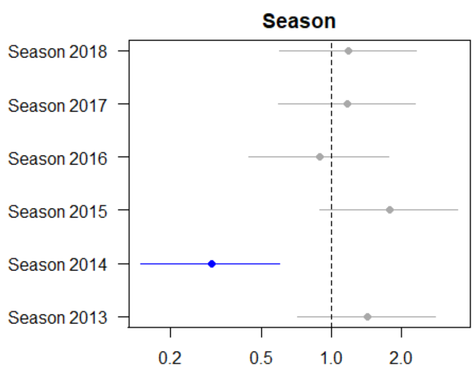


Figure 6~~6~~: By-season random effects. The dots indicate the mean OR whereas the line represents the 95% credible interval. Blue and red dots indicate OR that are significantly smaller or larger than 1 (i.e., credible interval does not cross 1).~~Same presentation as Figure 5.~~

~~3.6~~3.7 Limitations and future challenges

While the present results offer valuable quantitative insight into the relationship between avalanche hazard and run list codings at NEH, there are several potential avenues for exploring these relationships further and developing operational decision aids that offer value to ~~guides~~ guiding teams. While the present model only included a relatively crude representation of avalanche hazard (i.e., hazard rating and presence of avalanche problems), a more complete characterization of avalanche hazard according to the CMAH (Statham et al., 2018) could reveal more detailed insights about the suitability of runs under specific avalanche hazard conditions. For example, explicitly including aspect, the likelihood of avalanches and destructive size parameters of the existing avalanche problems in the run list model has the potential to extract more detailed information about the relationship between the avalanche hazard situation and the characteristics of runs with ~~acceptable~~ appropriate skiing terrain. Similarly, integrating more detailed ski run characteristics into the analysis might also help to reveal additional insight. Even though ~~it~~ using Sterchi and Haegeli's (2019) operation-specific ski run classes was a conscious choice ~~to use an operation-specific ski run classification to represent the nature of the terrain in the present study~~ to limit the complexity of this first quantitative analysis to a reasonable level, future research in this area will need to isolate the operation-specific intricacies so that the identified patterns between avalanche hazard and terrain that can be generalized across operations. However, taking this research to this level will require operational datasets of run list choices and avalanche hazard information that are substantially larger than the dataset used in the present study.

4 Conclusions

Using a large, multi-seasonal dataset of operational run list choices from a mechanized skiing operation, we applied a general linear mixed effects model to quantitatively explore the relationship between appropriate skiing terrain (i.e., open or closed for guiding) and avalanche hazard conditions at the run list scale ~~between avalanche hazard conditions and acceptable appropriate skiing terrain numerically~~ for the first time. ~~Mixed effects models including random effects are an adequate statistical tool for analysing terrain choices since they can properly account for the nature of the dataset with its repeated measures (i.e., panel structure).~~ Our model included an avalanche hazard rating and eight binary variables indicating the presence of different avalanche problem types as predictors and the class of the ski run, whether it was skied in the previous seven days and how it was rated on the previous day as covariates. In addition, ~~The model included~~ by-run and by-season random effects were incorporated into the model to account for the panel structure of the dataset.

Our results show that the effect of avalanche hazard on run list codes depends heavily on the type of ~~terrain~~ ski run that is being assessed and the nature of the avalanche hazard. While the run list ratings of the gentlest terrain are only marginally affected by hazard ratings, severe alpine terrain is especially susceptible to increasing avalanche hazard. Compared to the effect of the avalanche hazard rating, the effects of the different avalanche problem types on the run list codes are small but represent critical, ski run class specific adjustments. Our results also highlight the strong effect of recent skiing and thus experiencing the conditions and having recent first-hand field observations on run list codings. This result reflects the fact that guides reopen runs they have recently skied more quickly than other comparable runs. ~~Previous skiing is an important part of managing risk in heli-skiing as it is considered as a compaction and stabilization factor (Clair Israelson, personal communication, 2019).~~ The strong effect of the run code of the previous day highlights that terrain choices in mechanized skiing are evolving over the course of a season and further underline the necessity for analysing professional terrain choices in their temporal context.

While our results primarily confirm expectations, we believe this study provides a valuable step towards describing the terrain selection process at mechanized skiing operations numerically in a meaningful way. For the first time, the effect of avalanche hazard has been isolated from the influence of other factors such as the run list code the day before and the effect of recent skiing. Properly isolating these effects is critical for describing the relationship between avalanche hazard and ~~acceptable~~ appropriate terrain in a meaningful fashion. In addition to offering insight into the run list coding process, the present research also provides important context for the analysis of small-scale terrain choices in avalanche terrain (e.g., analysis of GPS tracks) since the terrain choices in mechanized skiing are made in stages and the decisions made in the field critically depend on the choices of eliminating unsuitable runs made during the preceding guide meeting.

In the long-term, this body of research will develop the foundation for the design of evidence-based operational decision aids that can help guides to make terrain choices more efficiently. It is important to note that we do not envision these decisions aids to actually make guiding decisions or be used for external auditing purposes like suggested by Hendrikx et al. (2016). However, if designed correctly, such decision aids may offer ~~an~~ independent references that allow~~s~~ guides to check their morning run lists against their own historical decisions under similar conditions. Furthermore, the knowledge gained from these models may create the necessary foundation for the development of evidence-based terrain guidance tools for recreationists in the future.

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6 Author contributions

RS, PH and PM co-led the design of this study. RS conducted the statistical analysis and authored the initial draft of the paper. PM consulted on the statistical analysis. RS, PH and PM subsequently edited the paper collaboratively to produce the final version of the paper.

7 Competing interests

The authors declare that they have no conflict of interest.

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