WHAT TYPE OF SKI RUNS ARE ACCEPTABLE FOR SKIING UNDER DIFFERENT AVALANCHE HAZARD CONDITIONS? EXTRACTING KNOWLEDGE FROM HELI-SKI GUIDES

Reto Sterchi and Pascal Haegeli

School of Resource and Environmental Management, Simon Fraser University, Burnaby BC, Canada

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KEYWORDS: Mixed effects model, avalanche risk management, terrain selection, decision making, helicopter skiing, conceptual model of avalanche hazard.

1. INTRODUCTION

Snow avalanches are the most significant hazard affecting daily operations in mechanized skiing in Canada (Bruns, 1996). Walcher et al. (under review) report that between 1997 and 2016 avalanches accounted for 77% of the overall natural hazard mortality in mechanized skiing in Canada. Operations manage this risk by assessing the local avalanche hazard 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.

The terrain selection process in mechanized skiing operations is well-established. It is iterative in nature and occurs at multiple spatial and temporal scales (Hendrikx et al., 2016). The daily process starts with a hazard assessment in the morning, which results in a large-scale avalanche forecast for the entire tenure. Subsequently, the guiding team evaluates their inventory of predefined ski runs and collaboratively decides what type of terrain is open or closed for guiding under the expected conditions. The resulting consensus-based “run list” guides the subsequent terrain decisions in the field by eliminating certain runs from consideration for the day. Throughout the day, terrain choices are further refined and adapted using real-time field observations. While avalanche hazard is one of the most critical factors 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 skied runs (Israelson, 2015).

While the steps of the terrain selection process are well defined, the relationship between environmental factors and the open/closed status of runs is much more complex and has so far only received limited attention from research. Grimsdottir (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. While Hendrikx et al. (2016) and Thumlert and Haegeli (2018) studied the association between small-scale terrain choices and avalanche conditions by analyzing patterns in GPS tracks, they did not consider the hierarchical and temporal context that the run list (or similar earlier large scale terrain choices) sets for the smaller-scale terrain choices.

The objective of our study is to address this knowledge gap by explicitly examining the relationship between acceptable skiing terrain (i.e., it being open 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.

* *Corresponding author address:*
Reto Sterchi,
School of Resource and Environ. Management, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada V5A 1S6
email: reto_sterchi@sfu.ca
web: avalancheresearch.ca

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. NEH's operating tenure is in the Skeena Mountains and spans an area of nearly 6,000 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).

2.2 Data set

The primary dataset used in this study consists of daily run lists and avalanche hazard information for the six winter seasons 2012/13 to 2017/18 (517 operational days). The run list dataset consists of more than 25,000 daily run ratings, each specifying that a run was either open or closed.

NEH's avalanche hazard assessment process follows the structure outlined in the conceptual model of avalanche hazard (Statham et al., 2018). In the present study we focus on their hazard ratings and their records of whether a persistent avalanche problem was present or absent. NEH assesses avalanche hazard at each elevation band on an ordinal scale from 1 (Low) to 5 (Extreme).

To describe the general nature of the ski runs included in this study, we employed the terrain classification developed by Sterchi and Haegeli (under review). In comparison to existing terrain classification systems with their small number of universal terrain classes (e.g., ATES; Statham et al., 2006), Sterchi and Haegeli's approach identifies high-resolution, operation-specific terrain hierarchies based on multi-seasonal patterns in run list ratings (i.e., revealed terrain preferences).

Sterchi and Haegeli (under review) identified six distinct terrain classes at NEH (Fig. 1). While the severity of terrain generally increases from Class 1 to Class 6, the groupings also reflect other run characteristics like accessibility, quality of skiing experience and operational practices. 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 Group 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. While the two runs included in Class 3 are generally of similar character, they are located at lower elevations, which makes them more susceptible to rising freezing levels. In other words, these runs quickly become unusable for the skiing program during warm spells. While most of the ski runs of the first three groups are at tree line and below, the next three groups 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 inclu-

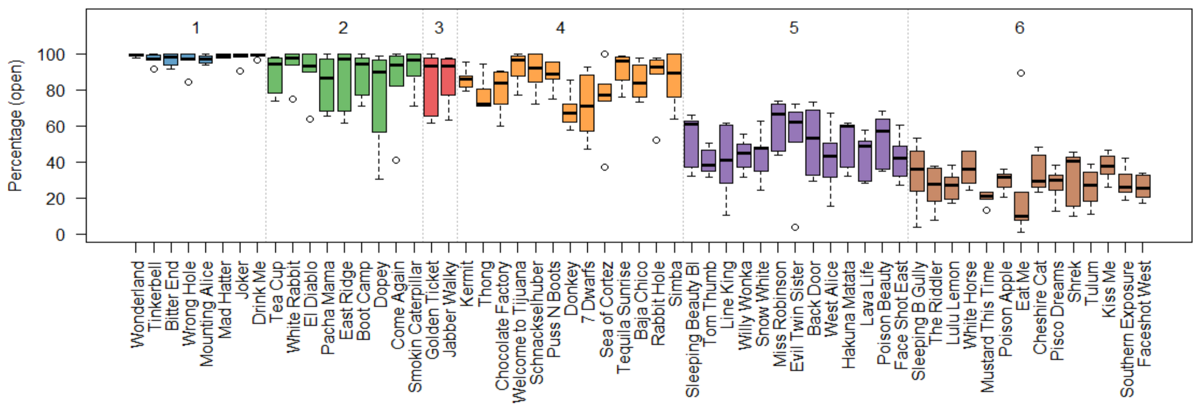

Fig. 1: Average seasonal percentage of run code 'open' for the 59 ski runs during the six seasons 2012/13 to 2017/18 included in our analysis with the six identified classes of similarly managed terrain types (Sterchi & Haegeli, under review).

ded in Class 5 are also located in the alpine, but they are substantially steeper and cross avalanche slopes more frequently than the runs of Group 4. Furthermore, almost half of the ski runs in Group 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, 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 line up. 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 regularly exposed to overhead avalanche hazard. However, they provide good or very good skiing experiences for the guests.

2.3 Mixed effects model

Since traditional regression models require observations to be independent from each other, they are inappropriate for analyzing longitudinal (i.e., repeated ratings of the same run) and/or clustered datasets (Long, 2012). Mixed effects models are an extension of traditional regression models that accounts for the correlation structure of such datasets by estimating so-called random effects in addition to the traditional regression coefficients (called fixed effects). While the fixed effects describe the relationship between the dependent and independent variables for the entire dataset, random effects describe the variability of the relationship among different groupings in the dataset.

To examine the acceptability of a run (i.e., it being open) under different hazard conditions, we regressed the daily run list codes of the run against the *Relevant hazard rating of the day* with the *Terrain type of the run* as a covariate. The binary nature of our run list codes determines that we use a logistic regression to model this relationship.

Relevant hazard rating of the day was determined by taking the highest hazard rating of the elevation bands crossed by each run. Since the effect of the hazard rating might differ depending on the type of terrain of a run, we also included the interaction effect of hazard and terrain type in the model. This allows the model to extract terrain type-specific relationships between run list code and hazard. A binary predictor describing the *Presence of a persistent avalanche problem* was also included in the model to highlight situations when avalanche conditions might have been particularly challenging.

In addition to the variables representing avalanche hazard and the nature of the terrain, we included *Skied in the last seven days* and *Run code of previous day* as additional predictors. *Skied in the last seven days* represents recent field observations and first-hand skiing experience on a run. *Run code of the previous day* was included to account for the autocorrelative structure of run lists from subsequent days. To better understand how these two predictors affect run list codes together, we included their interaction term in the model as well.

To account for the panel structure in our dataset, we included random by-run intercepts and slopes for hazard and for persistent problems, random by-terrain class slopes for persistent problems, as well as random by-season intercepts accounting for the character of each winter in the model.

We performed our analysis in R using the *lme4* package (Bates et al., 2015). While *Relevant hazard rating* and *Terrain types* were included in the model as a numeric and categorical variable, all other predictor variables were binary. However, all variables included in the model were scaled to range between 0 and 1. Models were evaluated following the information-theoretic approach of the Akaike information criterion (AIC; Akaike, 1974). Compared to pure goodness-of-fit measures that only assess how well the observed outcome is replicated by a model (e.g., R^2), the AIC also considers model complexity and penalizes models with larger numbers of parameters. Models with smaller AIC values are typically considered better. Only parameter estimates with p-values < 0.05 were considered significant and odds ratios (OR) are used to describe the effects of predictors. An OR > 1 means that the odds of a run being open are higher under the given scenario relative to a reference scenario.

3. RESULTS AND DISCUSSION

As a detailed description of all of our results is beyond the scope of this conference paper, we only provide an overview of the main results.

3.1 Effect of hazard rating and terrain type

As expected, the probability of a run being open decreases significantly with increasing hazard. On average, the odds of a ski run being open decreases by a factor of three for every step on the hazard scale. However, the magnitude of the overall effect of avalanche hazard depends significantly on terrain type (Fig. 2a). While the probability of being open with increasing hazard rating

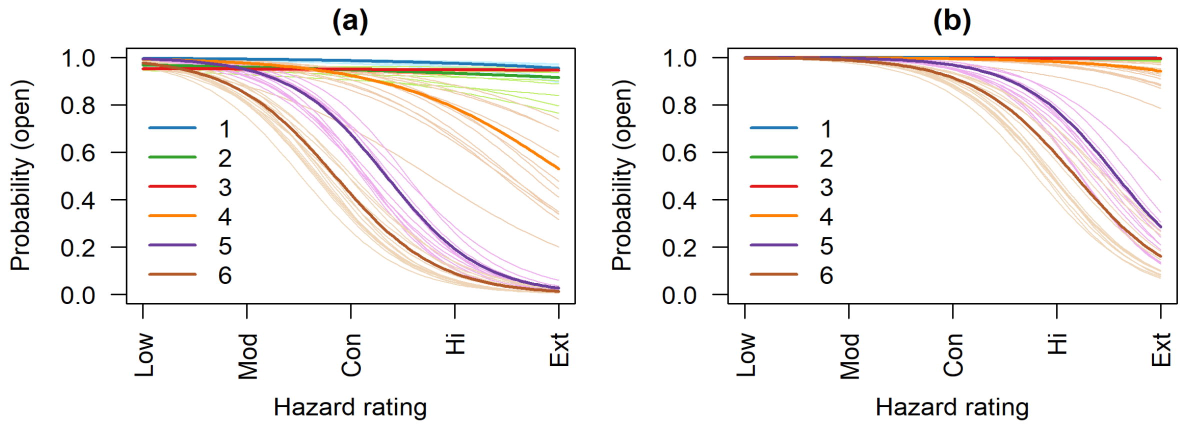

Fig. 2: Probability of runs (thin lines) from a certain type of terrain (thick lines) at NEH being open conditional on the hazard rating shown for an average season. (a) Shows the effect of increasing hazard when runs were open the day before, not recently skied and there are no persistent avalanche problems of concern, whereas (b) Shows the effect of increasing hazard when runs were open the day before, were recently skied and there are no persistent avalanche problems of concern.

only decrease marginally for runs of the first three terrain classes, the alpine terrain classes are affected much more strongly. This applies particularly for Classes 5 and 6, which are characterized by challenging alpine ski runs on steep and large slopes and have considerable exposure to overhead hazard.

The spread of runs in Fig. 2a further highlights that even individual runs are more or less affected by hazard in addition to what can be explained with the terrain type. In Class 6, for instance, the runs with large and steep avalanche slopes are even more conservatively coded than the runs that are moderately steep and have multiple small avalanche slopes. This effect is captured by the random by-run intercepts and slopes for hazard included in the model.

3.2 Effect of persistent avalanche problems

While the presence of a persistent avalanche problem exhibits the expected negative overall effect on run list codes in our model, the effect is not significant. However, the random effect for terrain types reveals that the run list codes of terrain classes 5 and 6 are affected more strongly by the presence of persistent slab problem. Furthermore, we find additional negative random effects at the run level, which we interpret as a sign for runs that are particularly susceptible to persistent avalanche problems. This primarily includes the most severe and unfriendly ski runs of Class 6.

3.3 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 last seven days have both a significant influence on it being open today (illustrated in Fig. 2b). Compared to a run that had not been skied during the last seven days and was closed yesterday, being open yesterday increases a run's odds of being open today by 30 times. The effect of having recently skied the run is even larger, as it increases the odds of a run that was closed yesterday to be open today by 54 times. Hence runs that have been skied in the recent past reopen more quickly. As expected the interaction of the two parameters shows that the combined effect of the two predictors is not as large as the sum of the individual effects. When a run was open the previous day, recent skiing increases the odds of being open only by 15 times. This is only about a quarter of the size of the effect when a run was closed the previous day.

These results illustrate the strong effect of the run list from the previous day as terrain choices evolve over the course of a season. 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 when runs were closed the previous day.

3.4 Seasonal differences

The random effect for season highlights seasonal differences in how runs are coded. For instance, runs were coded open only half as often during the low snowpack winter 2014 and the warmer-than-usual 2015 winter compared with the other seasons. These results highlight that having long-term datasets and properly accounting for it in the analysis approach is critical for identifying meaningful patterns in risk management practices as the particularities of individual winters can considerably affect observed choices.

4. CONCLUSIONS

Using a large, multi-seasonal dataset of operational run list choices in mechanized skiing, we applied a general linear mixed effects model to explore the relationship between avalanche hazard conditions and acceptable skiing terrain numerically for the first time. Our model included an avalanche hazard rating and whether a persistent problem was present as predictors and the terrain class of the run, whether it was skied in the last seven days and how it was rated on the previous day as covariates.

Our results highlight that the effect of avalanche hazard on run list codes depends heavily on the type of terrain that is being assessed. While the run list ratings of the most mellow terrain are only marginally affected by hazard ratings, severe alpine terrain is especially susceptible to increasing avalanche hazard. Random effects on the run level further highlight sensitivities of individual runs that cannot be explained with terrain type alone. Moreover, our results highlight the strong effect of recent skiing and thus experiencing the conditions and having recent first-hand field observations. This result reflects the fact that guides reopen runs they have recently skied more quickly than other comparable runs. 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 underline the necessity for analyzing professional terrain choices in their temporal context.

While our results primarily confirm expectations and offer limited new insight, we believe this study provides a valuable first step towards describing the terrain selection process at mechanized skiing operations numerically in a meaningful way. The next step in this research is to further advance our understanding by further exploring the patterns among the random effects to identify runs that are particularly susceptible to certain hazard conditions and develop models that relate their terrain characteristics to the relevant parts of the hazard assessments. The results of this research will create the necessary foundation for the development of meaningful decision aids for guiding teams and provide important context for the analysis of small scale terrain choices.

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