CAN WE DERIVE AN AVALANCHE TERRAIN SEVERITY RATING FROM OBSERVED TERRAIN SELECTION OF PROFESSIONAL GUIDES? A PROOF-OF-CONCEPT STUDY

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ABSTRACT: The physical risk from snow avalanches poses a serious threat to backcountry recreationalists and the winter backcountry recreation industry. Professional guides predominantly manage this risk by 1) assessing avalanche hazard through analysis of the local weather, snowpack, and recent avalanche patterns and 2) selecting appropriate terrain that limits exposure to the avalanche hazard. This process is primarily experience-based, relies considerably on non-explicit and non-formal knowledge, and employs intuitive decision practices. Can we measure such terrain selection decisions of professional guides to produce an avalanche terrain severity classification? We equipped lead guides at Mike Wiegele Helicopter Skiing throughout the 2014/15 and 2015/16 winters with GPS units creating a dataset of 10,592 tracked ski runs. The four main terrain parameters we analyzed were slope, vegetation, down-slope curvature (convexities or concavities), and cross-slope curvature (gullies or ridges). We applied an ordered logistic regression mixed effects model using the above parameters as independent variables and the guide's PM avalanche hazard forecast as the dependent variable. The guides skied steeper, less dense vegetation, and more convoluted slopes during lower avalanche hazard conditions. The parameter estimates of the regression model were used to combine the terrain raster data in a GIS to create an overall avalanche terrain severity classification. The overall avalanche terrain severity classification compared well to terrain previously classified according to the Avalanche Terrain Exposure Scale. This paper represents a proof-of-concept for how measured professional terrain choices can be analyzed to produce an avalanche terrain severity classification.

KEYWORDS: Terrain selection, helicopter ski guiding, avalanche risk management, avalanche hazard, GIS avalanche terrain classification.

1. INTRODUCTION

Selecting terrain that minimizes exposure to avalanche hazard is the primary risk management strategy for people travelling in the uncontrolled winter backcountry (ACMG, 1999). Klassen (2012) suggests that incorporating terrain selection advice into public avalanche information products will greatly improve route finding in the field by public recreationalists, thus reducing exposure to avalanche hazard. But what are the specific characteristics of mountain terrain that can be identified and selected to minimize exposure to avalanches?

Statham et al. (2006) created the Avalanche Terrain Exposure Scale ($ATES_1$[1]), which provided a framework to comprehensively evaluate, describe, and communicate the complexities of avalanche terrain specifically for recreational backcountry travel. This work differed from previous zoning and classification of avalanche terrain which was specifically developed for elements of a more static nature (e.g. CAA, 2002). $ATES_1$ has public communication and technical versions that focus on subjectively classifying overall seriousness of avalanche terrain for backcountry recreational trips as class 1 simple, class 2 challenging, or class 3 complex. $ATES_1$ uses 11 parameters containing many qualitative terms such as “mostly”, “limited”, “numerous”, etc. which work well when applied for its designed purpose of classifying backcountry trips, however, this subjectivity creates challenges for more objective analyses and mapping using Geographical Information Systems (GIS). The translation of $ATES_1$ into GIS mapping is further complicated because fundamentally $ATES_1$ provides ratings for linear routes through terrain whereas the GIS mapping perspective is generally more spatial. The $ATES_1$ terrain classification system is being adopted by numerous avalanche safety services around the world (e.g. Campbell et al., 2012; Gavaldà et al., 2013; Martí et al., 2013; Maartensson et al., 2013; Pielmeier et al., 2014).

The first attempt to use GIS to spatially classify avalanche terrain according to $ATES_1$ was done

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by Delparte (2008). She used a raster-based decision tree algorithm that showed vegetation density and slope angle as the most important parameters from $ATES_1$ useful in GIS analysis. Campbell and Marshall (2010) zoned large areas of western Canada according to $ATES_2$. Then Campbell et al. (2012) refined the zoning methodology, and Campbell and Gould (2013) proposed a more deterministic practical model for GIS zoning with $ATES_2$. The zoning methodology proposed by Campbell et al. (2012 and 2013) begins with GIS analysis and then suggests detailed field visits if high accuracy is required resulting in polygon classification of avalanche terrain. To date, this methodology has produced well over 8000 km^2 of zoned terrain at the basin scale of 100 m to 1 km which is useful for recreational trip planning and worker safety applications. However, Schweizer et al. (2003) suggest a spatial scale of 20-30 m is required for route finding in complex avalanche terrain, thus classifying avalanche terrain at this finer scale has potential for improvement in backcountry travel decision making.

Professional guides have been making semi-qualitative evaluation and selection of avalanche terrain to manage avalanche risk for centuries. The expert evaluation and subsequent selection of ski terrain employs intuitive decision practices, is primarily experienced-based, and relies on non-formal knowledge (e.g. Adams, 2005). The wealth of knowledge contained in the professional guiding community is vast, and the scientific community is just beginning to explore it (e.g. Grimsdottir and McClung, 2006; Haegeli and Atkins, 2010; Haegeli et al., 2010). A recent case study by Hendrikx et al. (2014) used GPS track data from helicopter skiing in Alaska to explore differences in terrain choices with changing avalanche hazard conditions. Using the observed behavior of professional guides to derive avalanche terrain classification provides an objective method that has the potential for analysis at the scale useful for decision making.

The guides at Mike Wiegele Helicopter Skiing (MWHS) regularly find safe routes through terrain that would be classified as complex according to $ATES_1$ during times of elevated avalanche hazard. Their detailed knowledge of the terrain and avalanche conditions combined with experience-based intuitive decision making enables them to qualitatively classify and select appropriate terrain. MWHS employs up to 11 helicopters during full operations in peak winter season which provides the opportunity for large amounts of terrain selection data. The objective of this study was to prove the concept of using guides terrain choices as a function of different avalanche hazard ratings to derive an avalanche terrain classification.

2. METHODS

2.1 Data collection and preparation

In order to use professional guide's terrain selection to derive an avalanche terrain severity classification, we tracked the lead guides at MWHS for the two winters 2014/15 and 2015/16 using GPS units. Only lead guides were tracked to capture the main terrain decisions made by the most experienced guides.

A comprehensive geodatabase system and a series of R packages (Haegeli et al., in prep.) were developed to process the raw GPS files, store the extracted run tracks as linear geometries and allow researchers to interact with the data. To characterize the nature of the terrain along the skied runs, we then extracted terrain specific raster data for slope, vegetation, down-slope and cross-slope curvature (resolution approximately 20 m) along the ski lines using the "extract" function from the R

Table 1: Terrain parameter classes

Incline class	*Value(˚)*	*Veg class*	*Value (stems/ha)*	*Down slope class*	Value	Cross slope class	Value
<18	<18	Treed	> 250	Planar	-0.1 to 0.1	Planar	-0.1 to 0.1
18 to 20	18-20	Sparse	26 – 250	Concave	> 0.1	Ridge	> 0.1
21 to 23	21-23	Open	=< 25	Convex	< -0.1	Gully	< -0.1
24 to 26	24-26						
27 to 29	27-29						
30 to 32	30-32						
33 to 90	33-90						

package “raster” (Hijmans, 2015). This produced an array of raster cells with terrain characteristic values for each of the tracked runs. The slope data were obtained from Natural Resources Canada Geogratis (Natural Resources Canada, 2015). The curvature data were derived from the slope raster using the curvature function from the Spatial Analyst toolbox in ArcGIS (ESRI, 2011). The vegetation data were obtained from the Vegetation Resources Inventory (Ministry of Forests Lands and Natural Resource Operations, 2015) in the form of stems per hectare of both live and dead trees.

Ordered classes were created for each of the numeric terrain variables (Table 1). We also recorded daily PM overall hazard ratings from the guides' meetings, skiing conditions, and flying conditions which were merged with the extracted terrain values of each of the raster cells. We also included a seasonal variable to account for the panel structure of the data. The resulting complete dataset consisted of 1,227,617 unique point values from 10,592 runs with corresponding date, season, elevation, aspect, slope, vegetation, down-slope and cross-slope curvature, flying conditions, skiing conditions, and PM hazard ratings. We then filtered the extracted terrain dataset to include only the 90^{th} percentile of slope inclines to focus the dataset on the most severe terrain the guides skied each day. To eliminate possible influences of other operational constraints, we also removed records collected when the flying conditions were recorded as “limited” or “inaccessible” and any data collected when skiing conditions were recorded as “avoided”. The filtered dataset consisted of 95,773 points from 3,959 runs.

2.2 Data analysis

To examine the relationship between characteristics of the most severe terrain skied and avalanche hazard, we used a mixed effects ordinal logistic regression model on the filtered dataset. The model estimated the probability of a given hazard rating based on the characteristics of the terrain skied, thus provided a good measurement of the relationship between terrain and the hazard rating. We used the “CLMM” function from the R package “ordinal” for the regression model (Christensen, 2015).

2.3 Spatial application and comparison

Given that part of our objective was expanding the classification of terrain according to avalanche severity from linear routes ($ATES_1$) to more spatial perspective ($ATES_2$), we applied the output of the model to create a spatial classification of the entire MWHS tenure. This was done for two primary reasons: first, practitioners interested in the results of this study are very used to the spatial display of data (maps), and second, a large area within the MWHS tenure has been mapped professionally according to $ATES_2$ (Campbell et al., 2012) which provided the opportunity to compare the model results with current avalanche terrain classification standards. Assuming that terrain deemed acceptable for skiing increases incrementally from higher lower hazard conditions, the cumulative probabilities produced by the model can be used to estimate the terrain deemed acceptable for skiing at each hazard level. Differences between cumulative probabilities can be used to highlight the terrain that is opened up at specific hazard rating improvement (e.g., from level 3 to 4).

Finally, we also used the output from the model to derive an overall avalanche terrain severity classification. This was done by applying the parameter estimates from the logistic regression model to the terrain rasters across the entire MWHS tenure and summing up the values for each raster cell. We compared the overall severity raster to the terrain that had been previously rated by professionals according to $ATES_2$ (Campbell et al., 2012) using the t-test.

3. RESULTS

The selected model included interaction effects between incline and vegetation and included the seasonal variable as a random effect:

$$\begin{aligned}\mathrm{logit}\big(\mathrm{P}(Y_i \le j)\big) = {} & \theta_j + \beta_1(incline_i) \\ & * \beta_2(vegetation_i) \\ & + \beta_3(down\ slope_i) \\ & + \beta_4(cross\ slope_i) + u(season_i) \\ i = 1,\ldots,n.\ j = 1,\ldots,J-1 & \qquad (1)\end{aligned}$$

where $\mathrm{P}(Y_i \le j)$ is the cumulative probability of the i_{th} rating falling in the j_{th} category or below, *i* are all the extracted terrain raster observations and *j* = 1 to 6 is the PM hazard rating; θ_j is the intercept for the *j*th cumulative logit, β_1 to β_4 are the regression parameters, and *u* is the random effect.

All coefficient estimates were significant at α = 0.05 (full model results not shown). The main effects for “incline” showed steeper slope classes associated with lower hazard conditions. “Vegetation” main effects were somewhat counter-intuitive indicating less vegetated slopes were associated with increased hazard conditions. However, the combined main and interaction effects for the “incline” and “vegetation” parameters exhibited the expected patterns of slopes above 26˚ for the “open” and “sparse” being skied under lower hazard conditions than “treed” slopes (lower hazard ratings are represented as higher parameter values in Figure 1). Both curvature parameters showed that more convoluted terrain was selected during times of lower hazard and that more planar slopes, in both down-slope and cross-slope directions, were preferred during times of elevated hazard. The trends from the model output indicate the guides skied steeper, less vegetated, and more convoluted terrain during period of improved avalanche conditions.

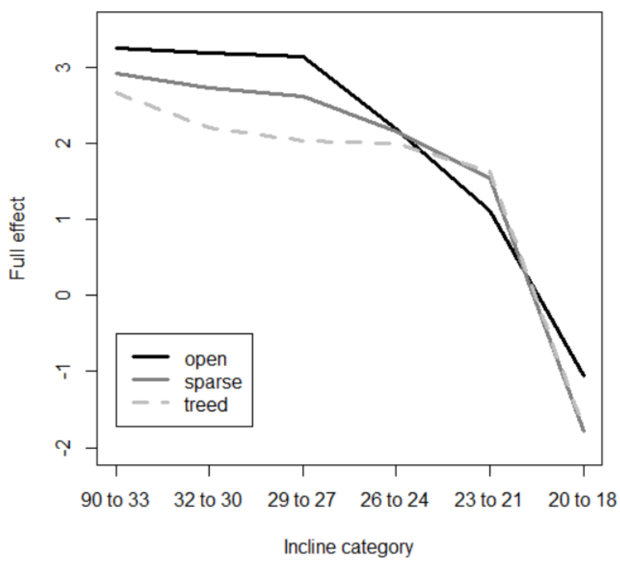

Fig. 1: The combined main and interaction effects between the incline and vegetation parameters from the ordinal logistic regression model.

Applying the model to the MWHS tenure results showed the guides deemed more severe terrain acceptable for skiing as the avalanche conditions improved (Figure 2 left panels). The right panels in Figure 2 display the specific terrain that “opens up” at each subsequent hazard level. Overall, the spatial probability plots (Figure 2) provide a tangible product from the regression model with more severe avalanche terrain (steeper, less vegetated, and more convoluted slopes) being represented by lower probabilities.

The median for the overall terrain severity classification was 1.4 for the entire tenure (interquartile range = -2.4 to 2.6). The overall avalanche terrain severity classification showed good agreement with the terrain that was professionally mapped according to $ATES_2$ (Figures 3 and 4). Figure 3 provides a visual comparison of how the simple, challenging, and complex areas relate to the terrain severity classification. There is good qualitative agreement between terrain rated as complex and the numeric terrain severity classification greater than 2. Further, terrain rated as simple according to $ATES_2$ mostly had a terrain severity classification of less than -2. This result is further shown in Figure 4 which compares notched boxplots of the avalanche terrain severity values for each of $ATES_2$ categories. There were significant differences in avalanche terrain severity values between all three terrain categories rated according to $ATES_2$ (t-test: $p<0.001$).

4. DISCUSSION

The model output made intuitive sense with what is generally considered as more dangerous avalanche terrain (e.g. McClung and Schaerer, 2006; Statham et al., 2006) represented by higher coefficient values. “Incline” showed the greatest impact on the model results of all the four terrain parameters with coefficient values spanning a larger range. The higher coefficients for the steeper incline classes indicated that the guides deemed steeper slopes more severe. These results were consistent with the model developed by Campbell and Gould (2013) who showed that incline was the most important parameter and that steeper slopes resulted in more complex terrain when classifying terrain according to $ATES_2$.

The main effects for “vegetation” are somewhat counter-intuitive with less vegetated terrain being associated with higher avalanche hazard. However, the complete picture is provided by the combined main and interaction effects for “incline” and “vegetation” (Fig. 1), which is dominated by the interaction effect. While there are limited differences among the vegetation categories for slope inclines below 26˚, the expected pattern that more open slopes require lower avalanche hazard clearly emerges for slope incline categories above 26˚. This observation clearly highlights the importance of including interactions in the analysis of terrain selection. The observed pattern is consistent with the common understanding that the release of

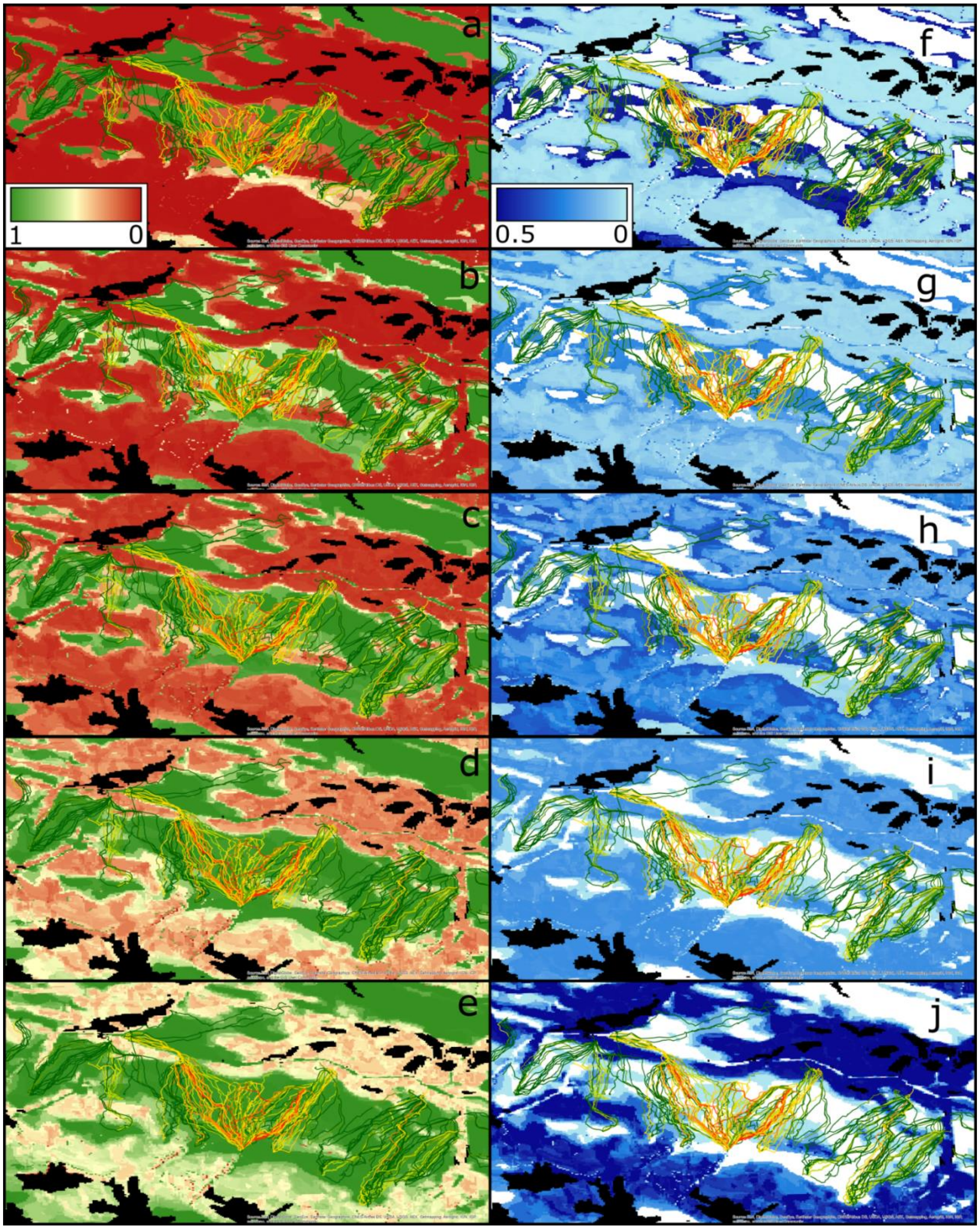

Fig. 2: A sample of the MWHS tenure with colored lines representing the lines the guides skied (color coded by the PM avalanche hazard rating with higher hazard represented as red and lower hazard represented by green). The left panels show the cumulative probabilities of a given avalanche hazard rating based on the terrain for a) hazard 1, b) hazard ≤ 2, c) hazard ≤ 3, d) hazard ≤ 4, e) hazard ≤ 5. The left panels can be thought of as a proxy for what terrain is "open" for skiing at a given hazard rating. The right panels show the individual probabilities of a specific avalanche hazard rating based on the terrain when f) rating improves from 1 to 2, g) rating improves from 2 to 3, h) rating improves from 3 to 4, i) rating improves from 4 to 5, and j) rating improves from 5 to 6. They can be thought of as what terrain "opens up" as the avalanche hazard improves by subsequent levels.

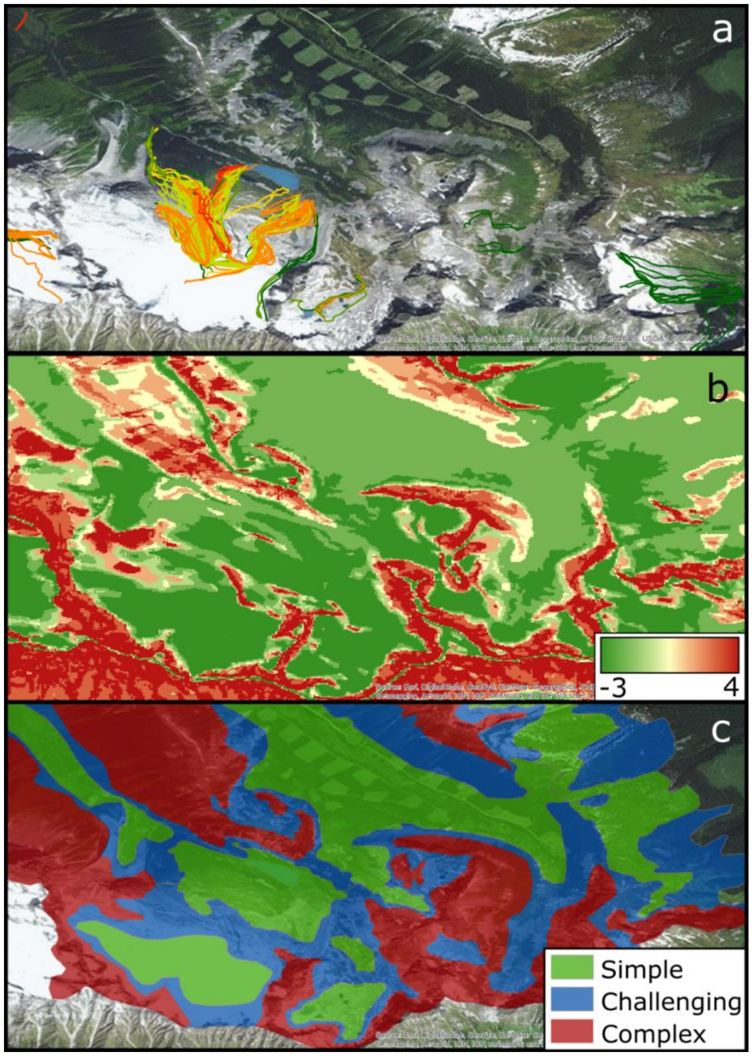

Fig. 3: A section of the MWHS tenure called Clemina Creek (image source: Esri 2016) with a) the GPS tracks from the guides shown as lines color coded as in Figure 2, b) the same section of terrain with the overall avalanche terrain classification calculated from the regression model output, and c) the professional terrain classification according to $ATES_2$ (Campbell *et al.,* 2012). Red was rated as "complex", blue as "challenging", and green as "simple".

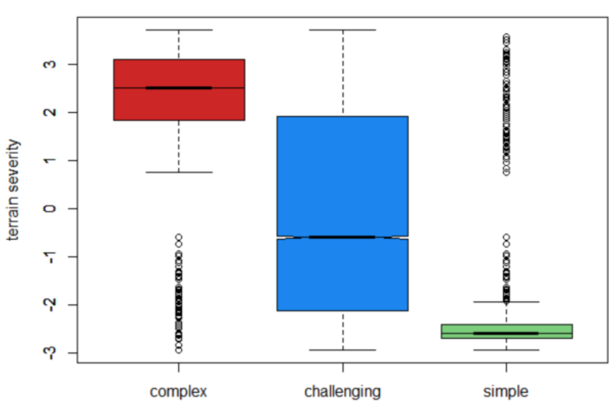

Fig. 4: Notched boxplots of avalanche terrain severity classification for each category of the professional $ATES_2$ terrain mapping (Campbell *et al.*, 2012) for the Clemina area of the MWHS tenure. Boxes span the interquartile range. Whiskers extend to the data point closest to 1.5 times the interquartile range. Outliers shown as circles. Notches are confidence intervals around the medians.

slab avalanches is very uncommon on slopes less than 25˚ (e.g. McClung and Schaerer, 2006; Jamieson et al., 2010). This result also agrees with Jamieson et al. (2010) who showed the vast majority of fatal avalanche accidents from a dataset of 95 avalanches occurring on open slopes (69 cases on open, 22 sparsely treed, 3 on mature timber) and 0% of the accidents on slopes less than 26˚.

The comparison of the overall terrain severity output to the portion of terrain previously professionally mapped according to $ATES_2$ showed excellent agreement. Capturing the behavior patterns of how MWHS guides manage avalanche hazard produced an indication of how severe guides perceive the terrain relative to avalanche risk. $ATES_1$ was created with much input from professional guides to qualitatively describe how exposed a specific linear route through avalanche terrain would be. Thus, the good agreement between the two approaches it is promising as they come at the problem from using different methodologies.

This first attempt to capture behavioral patterns of professional guides with respect to avalanche risk and then display them spatially shows good promise for classifying avalanche terrain. However, our initial model only included four terrain parameters compared to the 11 parameters described in $ATES_1$. Clearly the description of avalanche terrain is more complicated than four parameters, thus the results provided here are a simplification of a complex phenomenon. $ATES_1$ describes terrain with overhead avalanche hazard or terrain traps using five separate parameters: terrain traps, start zone density, interaction with avalanche paths, exposure time, and route options. We did not include overhead hazard or terrain traps in this analysis because currently there are no well-established GIS methods for identifying these terrain features. Developing the GIS capabilities to identify areas classified as terrain traps or terrain that is threatened by overhead avalanche hazard would be a valuable addition to future analysis.

The avalanche risk management system at MWHS referred to as the 5 Step System (Wiegele, 2012) uses a single overall hazard rating for each of the three main elevation bands. While there is much discussion during guides' meetings about the behavior of expected and observed avalanching, there are currently no explicit records of these discussions. Atkins (2004) proposed a list of avalanche characterizations which better capture the complexity of different avalanche hazard situations compared to the limitations of single overall hazard ratings. Atkins' ideas about avalanche character have been broadly adopted in North American avalanche communities through its integration in the Conceptual Model of Avalanche Hazard (Statham et al., in review). Avalanche character is an integral component for avalanche risk management as is dictates the type of required snow and weather observations, the predicted locations and impact pressures of avalanching, and much of the direct risk control practices. More specifically, in the case of guiding people through uncontrolled backcountry terrain, risk is mainly reduced by selecting appropriate terrain for the given avalanche conditions. Including avalanche character in future analysis would provide the opportunity for much deeper understanding of how professional guides manage the physical risk from avalanches through terrain selection under different types of avalanche problems. The derived terrain severity ratings would likely be strongly influenced by varying avalanche characterizations.

Including data from more winters would ensure that the terrain usage patterns would be more representative of an average winter. Further, the data presented here were collected from MWHS which lies on the western side of the Columbia mountains. Operational practices of MWHS have been developed to work well given the general character of the terrain and weather of the MWHS tenure. Care should be used when extrapolating these results to different mountainous areas. Future studies should include data from other geographic locations and from other professional guiding operations which would reduce any operational bias.

$ATES_1$ is being adopted in numerous countries as a methodology for describing avalanche terrain (e.g. Gavaldà et al., 2013; Martí et al., 2013; Campbell et al., 2012). Yet, there remain challenges applying $ATES_1$ with standardized specifications in a GIS (Campbell and Gould, 2013). Some of these challenges are likely because $ATES_1$ was developed by professional guides whose experience managing avalanche risk through terrain selection employs intuitive decision practices and relies on non-formal knowledge that is difficult to articulate in its full complexity (e.g. Adams, 2005). The approach presented in this paper avoids this issue by capturing the knowledge directly from actual terrain choices, the ultimate expression of guiding expertise. We believe that this new approach offer a promising direction for further study.

5. CONCLUSIONS

We tracked guides at MWHS for two winters with GPS units and analyzed their ski terrain decisions with respect to avalanche hazard with an ordered logistic regression model with mixed effects. We analyzed the terrain they selected with four parameters: slope incline, amount of vegetation in tree stems per hectare, and slope shape measured in down-slope and cross-slope curvature. The results showed that during lower avalanche hazard conditions steeper slopes, less dense vegetation, and more convoluted slopes were skied. The output from the regression model was used to capture the guide's terrain decisions with respect to avalanche hazard rating and then used to combine the four terrain parameters into an overall avalanche terrain severity classification. The avalanche terrain classification discriminated the three classes well for terrain that had been previously rated with $ATES_2$. This study can be seen as a proof of the concept of using the observed terrain selection behavior of guides to derive avalanche terrain classification.

ENDNOTES

[1] Here we refer to the Statham et al. (2006) original ATES terrain classification system specifically designed for linear backcountry trips through the terrain (denoted **$ATES_1$** throughout). We attempt to make the clear distinction between Statham et al. (2006) ATES and the Campbell and Marshall (2010), Campbell et al. (2012), and Campbell and Gould (2013) zoning according to ATES who expand the original linear ratings into a more spatial zoning (denoted as **$ATES_2$** throughout).

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REFERENCES

Adams, L., 2005. A systems approach to human factors and expert decision-making within the Canadian avalanche phenomena, Royal Roads University: pp. 284.

Association of Canadian Mountain Guides (ACMG), 1999. Technical Handbook for Mountain Guides. The Association of Canadian Mountain Guides, Canmore, AB, Canada.

Atkins, R., 2004. An avalanche characterization checklist for backcountry travel decisions. Proceedings of the 2004 International Snow Science Workshop, Jackson Hole, USA: pp. 462-468.

Atkins, R., 2014. Yin, Yang, and You. Proceedings of the 2014 International Snow Science Workshop, Banff, Canada: pp. 210-217.

Campbell, C., Marshall, P., 2010. Mapping exposure to avalanche terrain. Proceedings of the 2010 International Snow Science Workshop, Squaw Valley, USA: pp. 556-560.

Campbell, C., Gould, B., Newby, J., 2012. Zoning with the avalanche terrain exposure scale. Proceedings of the 2012 International Snow Science Workshop, Anchorage, USA: pp. 450-457.

Campbell, C., Gould, B., 2013. A proposed practical model for zoning with the Avalanche Terrain Exposure Scale. Proceedings of the 2013 International Snow Science Workshop, Grenoble, France: pp. 385-391.

Canadian Avalanche Association (CAA), 2002. Guidelines for Snow Avalanche Risk Determination and Mapping in Canada. Canadian Avalanche Association, Revelstoke, B.C., Canada.

Canadian Avalanche Centre (CAC), 2014. Avalanche Incident Report Database. http://www.avalanche.ca/cac/library/incident-report-database/view (accessed 30.07.15).

Christensen, R., 2015. Ordered - Regression Models for Ordered Data. R package version 2015.1-21. http://www.cran.r-project.org/package=Ordered/

Delparte, D., 2008. Avalanche terrain modeling in Glacier National Park, Canada. PhD thesis Department of Geography, University of Calgary, Canada.

ESRI, 2011. ArcGIS Software. www.esri.com/products/index.html (accessed 06.07.11).

ESRI, 2016. ArcGIS satellite imagery. www.esri.com/products/index.html (accessed 28.07.16).

Gavaldà, J., Moner, I, Bacardit, M., 2013. Integrating ATES into the avalanche information in Aran Valley (Central Pyrenees). Proceedings of the 2013 International Snow Science Workshop, Grenoble, France: pp. 381-384.

Grimsdottir, H. and McClung, D., 2006. Avalanche Risk During Backcountry Skiing – An Analysis of Risk Factors. Natural Hazards 39: pp. 127-153.

Haegeli, P., in prep. Methodology for isolating guide's ski lines from GPS data.

Haegeli, P., Atkins, R., 2010. Insights into the 'it depends' quantitative explorations of the assessment expertise of mountain guides. Proceedings of the 2010 International Snow Science Workshop, Squaw Valley, USA: pp. 130-132.

Haegeli, P., Wolfgang, H., Longland, M., Beardmore, B., 2010. Amateur decision-making in avalanche terrain with and without a decision aid: a stated choice survey. Natural Hazards 52:185.

Hendrikx, J., Shelly, C., Johnson, J., 2014. Tracking heli-ski guides to understand decision making in avalanche terrain. Proceedings of the 2014 International Snow Science Workshop, Banff, Canada: pp. 1021-1027.

Hijmans, R., 2015. Raster: Geographic Data Analysis and Modeling. R package version 2.3-40. http://CRAN.R-project.org/package=raster

Jamieson, B., Haegeli, P., Gauthier, D., 2010. Avalanche Accidents in Canada, Volume 5: 1997–2007. Canadian Avalanche Association, Revelstoke, BC, Canada.

Klassen, K., 2012. Incorporating terrain into public avalanche information products. Proceedings of the 2012 International Snow Science Workshop, Anchorage, USA: pp. 209-213.

Klassen, K., Haegeli, P., Statham, G., 2013. The role of avalanche character in public avalanche safety products. Proceedings of the 2013 International Snow Science Workshop, Grenoble, France: pp. 493-499.

Martí, G., Trabal, L., Vilaplana, J., García-Sellés, C., 2013. Avalanche Terrain Exposure Classification for Avalanche Accidents in Catalan Pyrenees. Proceedings of the 2013 International Snow Science Workshop, Grenoble, France: pp. 1100-1105.

McClung, D., Schaerer, P., 2006. The Avalanche Handbook. The Mountaineers, Seattle, WA: pp. 272.

Ministry of Forests, Lands and Natural Resource Operations, 2011. VRI – Vegetation Resource Inventory. http://catalogue.data.gov.bc.ca/dataset/vri-forest-vegetation-composite-polygons-and-rank-1-layer (accessed 01.04.2015).

Natural Resources Canada, 2015. Geogratis free data – Geospatial data extraction. http://geogratis.gc.ca/site/eng/extraction (accessed 01.04.2015).

Pielmeier, C., Silbernagel, D., Dürr, L., Stucki, T., 2014. Applying the avalanche terrain exposure scale in the Swiss Jura mountains. Proceedings of the 2014 International Snow Science Workshop, Banff, Canada: pp. 883 - 889.

Schweizer, J., Jamieson, B. and Schneebeli, M., 2003. Snow avalanche formation. Reviews of Geophysics, 41(4): pp. 2.1-2.25.

Statham, G., McMahon, B., Tomm, I., 2006. The avalanche terrain exposure scale. Proceedings of the 2006 International Snow Science Workshop, Telluride, USA: pp. 491–499.

Statham, G., Haegeli, P., Birkeland, K., Greene, E., Israelson, C., Tremper, B., Stethem, C., McMahon, B., White, B., and Kelly, J., *in review.* A conceptual model of avalanche hazard. Proceedings from the 2010 International Snow Science Workshop, Squaw Valley, USA: pp. 686.

Wiegele, M., 2012. Avalanche forecasting for safe travel in the backcountry: the 5-step checklist. Proceedings of the 2012 International Snow Science Workshop, Anchorage, USA: pp. 157–160.