TERRAIN SELECTION AND FORECASTED AVALANCHE DANGER: DO RECREATIONISTS SELECT SAFER TERRAIN WHEN THE FORECASTED AVALANCHE DANGER INCREASES?

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ABSTRACT: Backcountry winter recreationists move through landscapes differently depending on myriad factors, including mode of travel (e.g., backcountry skier vs. snowmobiler), skill level, fitness level, familiarity with terrain, snowpack conditions, group dynamics, etc. One factor that may influence a recreationist's terrain selection is the forecasted avalanche danger. Do recreationists select safer terrain when forecasted danger increases? To untangle this complex question, we analyzed a diverse dataset of GPS point locations (*n* = 2,305,766 points from 2,045 individual tracks) from winter recreationists in Colorado, USA over four seasons (2010 to 2013). Points were assigned a danger rating (North American Scale, Low to Extreme) based on the date of the trip and one of 24 possible combinations of aspect and elevation zones used for delivering the forecast to the public at the time. Points were assigned terrain variable attributes based on their location at several spatial scales, including elevation, slope angle, curvature, slope position, aspect, terrain roughness, heat loading, and percent tree canopy cover. In addition to characterizing the terrain for each forecasted danger category (e.g. low vs. considerable), we also compared terrain variables between modes of travel (backcountry skier/rider, snowmobiler, and hybrid motorized-assisted skier/rider groups), and between recreation in three forecast zones. Results from statistical tests suggest small differences in terrain selection under various avalanche forecasted danger levels, though terrain choices are not necessarily more conservative as forecasted danger increases. Objectively measuring recreationist movement patterns in avalanche terrain benefits educators and researchers interested in characterizing recreationist terrain selection and risk acceptance.

KEYWORDS: Terrain selection, GPS tracking, Recreation, GIS, Danger scale, Avalanche terrain

1. INTRODUCTION

Backcountry winter recreation in Colorado, USA is an increasingly popular activity (Bowker et al., 2012). Much of this recreation occurs in mountainous terrain prone to recreationist-triggered avalanches. Avalanche fatalities in the United States have been increasing since records began in the 1950s with an average between 25 and 30 fatalities per year since 2010 (CAIC, 2018). Colorado consistently has the greatest number of fatalities in the nation with an average of five to seven people dying per year since 2010 (CAIC, 2018). The majority of these fatalities are from recreationists skiing, snowboarding, snowmobiling and climbing in backcountry terrain (Logan and Witmer, 2012).

The Colorado Avalanche Information Center (CAIC) produces daily avalanche hazard forecasts for 10 geographic zones throughout Colorado. The forecasts highlight specific problems in the snowpack as well as assign a danger rating based on the North American Public Avalanche Scale (Low, Moderate, Considerable, High and Extreme) for 24 combinations of terrain aspect and elevation) (Statham et al. 2010). One important element in the danger rating is travel advice for recreationists in avalanche terrain.

Research is needed on how recreationists move through avalanche terrain under various hazard conditions to understand whether forecasts are effectively influencing safer terrain selection. However, there are limitations with the reliability of recreationists to self-report their movement patterns and terrain choices (e.g., Cole and Daniel, 2003; D'Antonio et al., 2010; Hallo et al., 2012; Marengo et al., 2016).

Passive tracking of recreationists with portable GPS receiver units to objectively characterize how winter recreationists move through backcountry terrain has gained interest among researchers in the United States and Europe in recent years (Bielański et al., 2018; D'Antonio et al., 2010; Miller et al., 2017; Olson et al., 2017), including the documentation of terrain selection by heli-ski guides in the United States and Canada (Haegeli and Atkins, 2016; Hendrikx et al., 2015; Hendrikx and Johnson, 2014; Hendrikx et al., 2013; Thumlert and Haegeli, 2018; Thumlert and Haegeli, 2016). These studies found GPS data

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helpful in describing movement patterns by guides, especially when coupled with site-specific snowpack information and operational data such as the participant's familiarity with the terrain and group demographics.

The largest recreationist and avalanche terrain study to date that includes all winter recreation types, the "SkiTracks" and subsequent White Heat Tracks project (Hendrikx and Johnson, 2014; Hendrikx and Johnson, 2016), found that recreationists move through terrain differently depending on their skill and experience level and group demographics. Hendrikx and Johnson (2016) also explored the relationship between terrain variables such as slope angle selected by recreationists while in the backcountry under various forecasted danger ratings, noting the challenges in working with only a few terrain variables to describe complex terrain decisions. Thumlert and Haegeli (2018) constructed a robust statistical model using terrain variables fundamental to hazard mapping and rooted in the Statham et al. (2006) Avalanche Terrain Exposure Scale (ATES) framework (slope angle, slope curvature, and landcover) and GPS tracks to quantify terrain selection amongst professional guides. Their modeling suggests guides do select terrain differently depending on specific hazard information.

We build on previous work with a broad view on recreationist movement in avalanche terrain by employing a large, geographically diverse dataset of recreation movement and link the time and location of where the recreation occurred to the forecasted danger rating for that location, on that day, to ask fundamental questions about recreationist terrain selection. We use a suite of terrain variables at several spatial scales including elevation, slope angle, slope curvature, terrain position, aspect, terrain roughness, topographic heat loading, and percent tree canopy cover, coupled with recreation data from three discrete groups of recreationists (snowmobilers, hybrid motorized-assisted skiers/riders and skiers/riders) captured from three CAIC forecast zones (North San Juan, South San Juan and Vail/Summit County) to investigate whether recreationists select safer terrain as the forecasted avalanche danger rating increases. Our analysis also includes both uphill and downhill travel by recreationists, accounting for the entire trip in the backcountry.

Here, we present a subset of the analysis and focus on testing a broad hypothesis: Do recreationists, irrespective of mode of travel or forecast zone, select more conservative terrain as forecasted avalanche danger increases?

2. METHODS

2.1 Data collection

Winter recreation movement data, which were captured as part of a larger winter recreation and wildlife study, were collected in the Vail Pass area of Central Colorado and the San Juan mountain range in southwest Colorado between 2010 and 2013 (Figure 1).

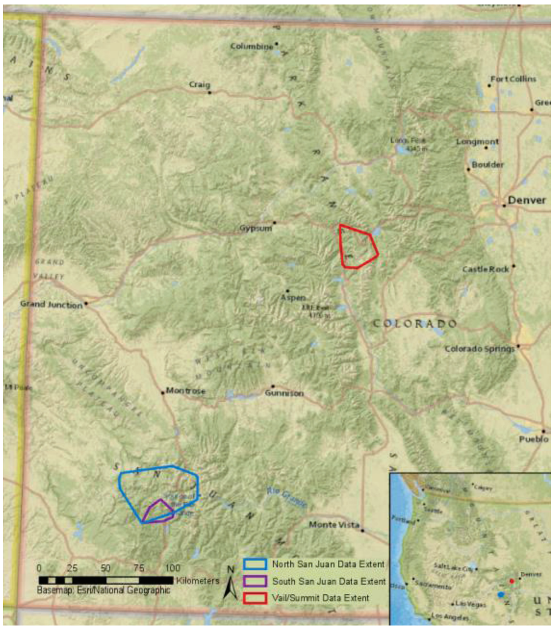


Figure 1: Map of study sites in Colorado, USA: Minimum bounding geometry of point locations included in analysis.

Sampling of backcountry access portals occurred between January and March of each season. Recreationists were approached at backcountry access portals and asked if they would carry a passive GPS device (Qstarz, model BT-Q1300, position accuracy <10m, logging frequency of 5-sec). They carried the GPS unit for their entire trip and it was dropped off, at which point track data were downloaded. Since recreationist anonymity (objectively capturing recreationist movement) was fundamental to the design of the larger study, no demographic or avalanche training or terrain familiarity information was recorded, however the mode of travel and group size were documented for each GPS track. Only one GPS unit was carried per group. For a full account of research sampling and design, see Olson et al. (2017).

2.2 Data pre-processing

A total of 2,305,766 points from 2,045 individual tracks were included in the analysis. The Vail/Summit zone had the most points (1,464,112 from 900 tracks), followed by the N. San Juan zone (737,877 points from 1,073 tracks) and the S. San Juan zone (103,777 points from 119 tracks). Figure 2 shows the distribution of points based on forecast zone and mode of travel, characterizing the broad recreation pattern of the sampled locations.

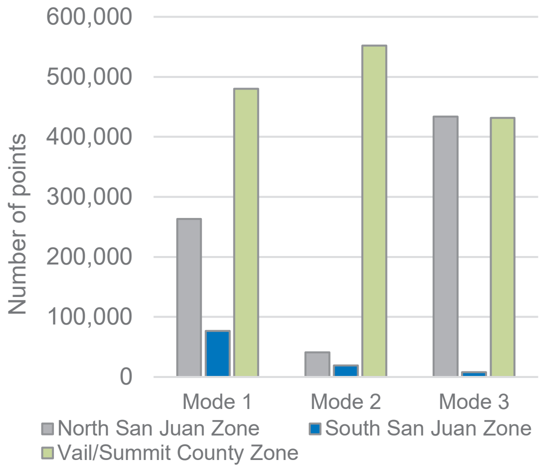


Figure 2: Distribution of points used in analysis based on mode of travel (Mode1: snowmobile, Mode 2: hybrid, Mode 3: backcountry ski/ride, and colored by forecast zone.

The point data were then classified based on the 24 combinations of elevation and aspect (e.g., northeast, above treeline) from the CAIC categories using a digital elevation model (DEM) (USGS NED, 10m). Treeline is not a fixed elevation changing with latitude and aspect, as well as local climate. For this classification, the “near treeline” category covered the range of treeline elevation estimates in Elliott and Baker (2004) for the San Juan zones (“near treeline” was 3550m-3650m), and in Elliott (2012) for the Vail/Summit zone (near was 3400m-3500m).

Each point was then assigned a danger rating based on the date the GPS point was fixed and corresponding to the forecasted danger rating low (1) to extreme (5) for that combination of elevation and aspect (data generously provided by CAIC). Points were then assigned terrain variables based on their location derived from a 10m DEM for elevation, slope angle, slope curvature, terrain position, aspect, terrain roughness, topographic heat loading. Percent tree canopy cover (Homer et al., 2015; 30m resolution) was also included. Several spatial scales were used in the analysis for some variables to identify sensitivities. For example, with slope position, the Terrain Position Index (TPI) was used (Evans et al., 2010) at a local 3x3 cell neighborhood to capture movement over and around small terrain features as well as a medium-scale 125m circular neighborhood to identify landscape features like ridges and gullies. Also, several approaches to quantifying slope and aspect were used. We linearized aspect into measures of northness and eastness (Evans et al., 2014) and used the Heat Load Index (McCune, 2007) which folds aspect based on the direction of the sun, taking slope angle into account to identify more- and less-solar aspects.

2.3 Data analysis

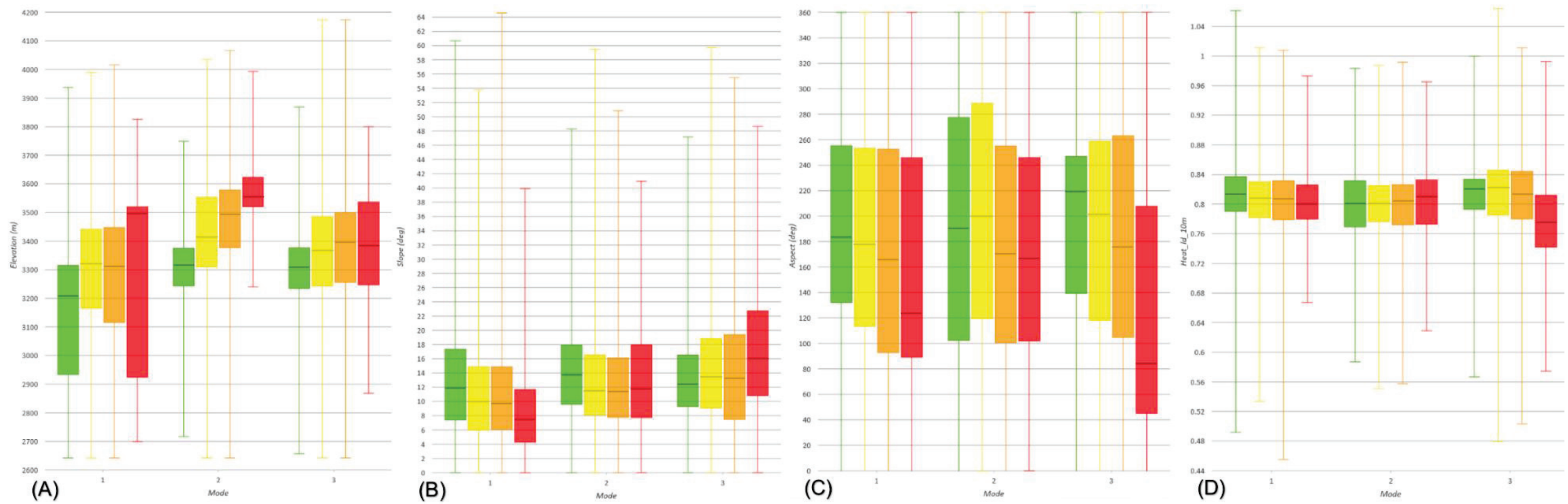
We used a parametric (contrasted one-way ANOVA with Tamhane’s correction for unequal variances) test at the $p < 0.05$ level. For comparison, we also used a nonparametric (Kruskal-Wallis, at same significance level) test. In both cases we tested for differences in the means of terrain variables for each mode of travel between low, moderate, considerable and high danger ratings. There were no extreme danger rating points in our sample. Because of the large sample size of the dataset and the unequal distribution of points in each danger category, we also randomly selected 5000 points from each danger rating category for each mode, tested these subsets against each other for significant differences, and repeated this 10 times with new random sub-samples.

We also tested variables with a collapsed danger rating (Low + moderate vs. considerable + high) using the Mann-Whitney U Test at $p < 0.05$. Finally, like in Hendrikx and Johnson (2016), we also investigated the differences in danger rating among a subset of point data that were on the steepest parts of the tracks. We compared terrain variables for points that had a slope value above the 95th percentile.

3. RESULTS AND DISCUSSION

Here we present only a subset of the analysis results focusing on the main hypothesis presented here. The distribution of points in each danger rating category for each mode of travel are shown in Figure 3. Results from both statistical tests found all variables had significantly different means for the danger rating categories, for each mode, except terrain roughness and local TPI. However, both the differences in mean values and effect sizes were small and the terrain variable distributions for each danger rating category are large. In other words, no matter the forecasted danger rating recreationists may alter their terrain selection, but they still move through a wide range of terrain features. From this analysis, we cannot clearly see that recreationists become more conservative as the forecasted danger rating increases. Figure 3 provides examples of terrain variable distributions and a map of data from the N. San Juan zone showing backcountry skiing/riding points colored by their danger rating value.

These results are important for three main reasons. First, the broad pattern is similar for all three modes and forecast zones: The vast majority of recreation (90%) occurred in a location with a moderate or considerable forecasted danger. This mirrors a typical snowpack in Colorado (danger rating mean for all days, aspect/elevation zones during sampling was 2.14 compared with



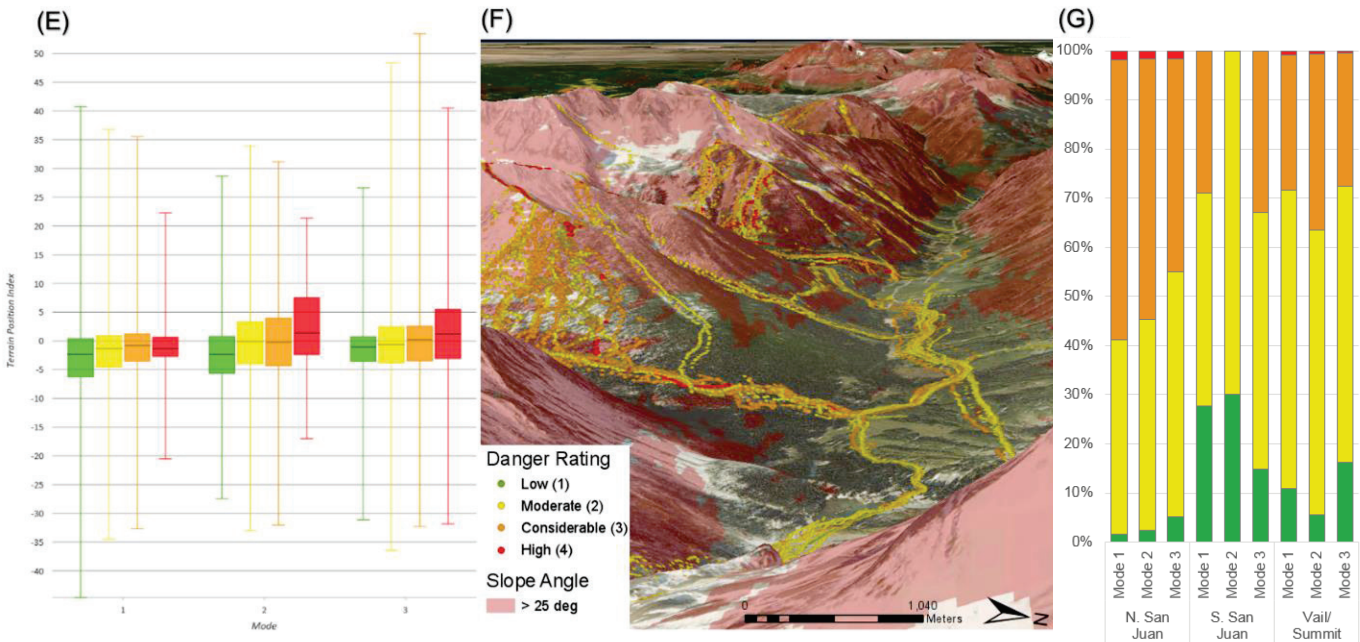


Figure 3: Boxplots (median, min/max, 1st/3rd quartiles) for example terrain variables, including (A) elevation (m), (B) slope angle (deg), (C) slope aspect, (D) heat load index (highest values are southwest solar aspects), (E) terrain position index (medium scale neighborhood: positive value is concave such as ridges) for snowmobile (mode 1), hybrid (mode 2) and backcountry ski/rider (mode 3) segmented by danger rating. Colors denote danger category from left to right: green is low, yellow is moderate, orange is considerable, red is high. Example map (F) of point data classified by danger rating, colored as above, with slopes >25 deg in red shading, from N. San Juan forecast zone (note: scale bar represents linear scale in center of scene). Distribution of points (G) in each danger category for each mode across all three forecast zones, colored as above from low (bottom) to high (top).

2.29 for all observed recreation). For each mode in each zone, there were more moderate points than considerable, except in the N. San Juan zone where both the snowmobile and hybrid groups had more considerable points. There were relatively few high danger points (0.98% of all recreation data).

Second, regardless of the danger rating, recreation occurred on a wide range of aspects and slopes. For all modes, the majority (85%) of recreation occurred on slopes with an angle of less than 20 degrees. However, the tails of these distributions offer important insight into risk acceptance. For all three modes a small percentage of overall recreation (1.6%) occurred on steep slopes (95^{th} percentile, or greater than 27.4deg) when the danger rating was considerable or high. Despite the small percentage of overall points, there were 903 tracks (44% of all tracks) that included travel on a steep slopes that were forecast to have a considerable or high danger rating. While this finding is very specific, it suggests that even recreationists selecting low angle terrain when danger is higher may still move through risky terrain during their trip. On average, only 3.6% of the points along a typical track were on steep slopes with a forecasted rating of considerable or high. Most considerable danger points were on low-angle terrain.

Third, in addition to slope angle, additional terrain variables can help characterize recreationist movement through avalanche terrain. For example, terrain position index gives both a local measure of convexity/concavity, as well as a medium scale, drainage-level measure of slope convexity/concavity that can identify ridges, gullies, and open slopes. Additionally, the heat load index can quickly identify recreation on sunny (southwesterly) slopes and darker (northeasterly) slopes. Using these variables, we can, for example, compare mean danger ratings for backcountry skier/rider points found on ridges (95^{th} percentile TPI, mean = 2.42) compared to the lowest TPI points found in gullies (mean = 2.36). Together with traditional terrain variables such as slope angle and local curvature, these variables provide a more comprehensive characterization of recreationist terrain selection.

3.1 Limitations and future directions

We use forecasted avalanche danger as a proxy for the actual danger. It is not possible, from these data, to directly relate actual danger to the terrain selection of recreationists. We have simplified terrain selection, and by extension terrain selection, into the terrain variables we can analyze with a Geographic Information System. Real-world decision making is much more complex than this. However, providing an objective measure of recreationist movement does provide an important perspective on risk acceptance. The analysis is also limited by the spatial resolution of the 10m DEM used here. While a 1m DEM is available for the Vail/Summit County zone, the precision and accuracy of the GPS units make its utility in subsequent terrain analysis limited. We did extract elevation and slope values from the 1m DEM for the recreation in the Vail/Summit County zones and compared the measurements to the 10m data. Differences were negligible. For consistency we used the 10m DEM for the full analysis. Finally, working with spatial data introduces additional statistical complexity over non-spatial data. We have kept the statistics simple for this analysis, but more robust analysis is needed to fully characterize recreationist terrain selection since the data, while sampled independently, still exhibit strong spatial autocorrelation, which suggests other terrain and/or non-terrain variables are likely influencing terrain selection.

4. CONCLUSION

This analysis provided a broad characterization of recreationist movement through backcountry terrain and related that movement to the forecasted avalanche danger for that location. Understanding recreationist risk acceptance in avalanche terrain is complex. However, the analysis builds on previous studies, with sampling from a wide swath of winter recreationists, to provide insight into key terrain variables that characterize terrain selection. There is a range of risk acceptance among recreationists sampled. More work is needed to dissect the terrain selection of the most risk-accepting recreationists and couple this with more direct measures of avalanche danger.

ACKNOWLEDGEMENT

Thank you to the CAIC for the forecast data, the research staff who collected data and study participants who volunteered to carry a GPS unit.

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