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Tracking decision-making of backcountry users using GPS tracks and participant surveys

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ABSTRACT

Snow avalanches are a significant natural hazard representing the primary risk of death to backcountry travelers in many alpine countries. Careful use of backcountry terrain through effective decision making can mitigate the risk of dangerous snowpack conditions, but requires relevant knowledge and experience.

We present the results from a large-scale crowd sourced data collection method from backcountry users. Using GPS tracking via a smartphone application, coupled with online surveys, we investigate the intersection of geographical complexity, backcountry experience, demographics and behavioral biases on decision-making while navigating hazardous winter terrain. We use data from 770 GPS tracks, representing almost 1.3 million GPS points, as a geographic expression of a group's resulting decisions, and use them to quantify and understand their decision-making process.

Our analysis focuses on the change in terrain use as quantified using the Avalanche Terrain Exposure Scale (ATES), and time spent in avalanche terrain, as a function of experience, avalanche hazard and other group factors. We show that self-identified experts rate themselves as significantly more skilled and also had higher levels of avalanche education. Experts also had an increased exposure to avalanche terrain overall, and also more severe terrain, as represented by median time in class 3 ATES terrain.

1. Introduction

Snow avalanches are significant natural hazard, and represent the primary risk of death to backcountry riders (i.e. skiers and snowboarders) and snowmobilers in North American and many European alpine countries. In the USA, avalanches kill an average of 28 people per year (CAIC, 2021), and many hundreds worldwide (Techel et al., 2016). The majority of these deaths, especially in the USA and Europe are in a backcountry setting, that is; skiing practiced outside of designated ski areas and resorts (also known as out-of-bounds skiing). This activity has increased in popularity over the past several decades. Exact known growth rates of users are problematic but Birkeland et al. (2017) suggests, using a variety of indicators, that the total number of users is growing substantially. Avalanche-caused death rate is decreasing or stabilizing over time (e.g., Birkeland, 2016; Birkeland et al., 2017; Jekich et al., 2016).

In approximately 90% of cases the victim or a member of the victim's group is the triggering mechanism (e.g. McCammon, 2000; Schweizer and Lütschg, 2001) so the strategy of avoidance of backcountry terrain to mitigate or eliminate the risk posed by dangerous snowpack conditions could be highly efficacious. This also makes avalanches unique with respect to other natural hazards, as humans have a direct impact on the likelihood of these events occurring (unlike other natural hazards such as earthquake or tsunami). A complete understanding of avalanche risk must account for the geophysical (i.e. snowpack and terrain) and human factors (i.e. the decision-making processes that result in a triggering event). This means that relevant knowledge and experience at terrain management can likely influence the probability of being involved in an avalanche. To date, most studies on decision-making in avalanche terrain have focused on two areas; post-accident analysis using accident reports/interviews (e.g. Atkins, 2000; McCammon, 2002) and, the development of tools as decision forcing aids (e.g. Haegeli et al.,

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2010). Both methods inform our understanding of accident causes but do not help our understanding of the decision process of negotiating complex topography.

This paper presents the results from our crowd sourcing data collection of combined GPS and survey data that investigate how human decisions are made as groups negotiate complex terrain in natural settings. The wider background, data collection methods and preliminary results have been presented in Johnson and Hendrikx (2021). This paper focuses on the detailed analysis of these data with further detailed descriptions, an updated terrain analysis using the Avalanche Terrain Exposure Scale (ATES) rating (Statham et al., 2006) for large areas, and the use of a Generalized Classification Tree (GRT) to provide a more nuanced and detailed presentation of our results.

To review, we use a combination of a user submitted GPS track of terrain used by backcountry skiing participants, snowpack hazard assessment from their survey and local avalanche danger ratings (if available) and terrain characteristics using 10m Digital Elevation Model (DEM). This data is coupled with user surveys to help us understand decision making process and outcomes in close to real-time and without the biases inherent in post-hoc accident analysis (Johnson et al., 2020). The intent of this methodology is to utilize mixed methods of data collection and complementary secondary geospatial data to understand how small groups of travelers in the winter backcountry use a combination of topographic, environmental, and hazard elements to negotiate a safe and efficient route in a high-risk/low probability environment and integrate demographic and trip-based behavioral motivations into the decision-making process. The problem, as outlined in Johnson and Hendrikx (2021), is that it is increasingly understood that flawed decision-making processes by small groups moving through potentially hazardous terrain is, in part, responsible for avalanche accidents. At the same time, it is methodologically problematic to track such decisions in the terrain by small groups. Our data collection workflow and subsequent analysis seek to address both issues.

2. Background and theory

2.1. Changing approach to natural hazards

Natural hazards have primarily been viewed as phenomena of the geographical and biological domains and research has attempted to enhance the understanding of the physical system to decrease the incidence of human misfortune that results from, for example, extreme weather events or catastrophic geological forces. Consequently, much of the social science research in the field of natural hazards has focused on the societal vulnerability (i.e., macroeconomic costs, infrastructure resiliency) and the role of policy level intervention (i.e., planning and zoning laws, building standards) on minimizing exposure to, and increasing adaptive capacity to, natural hazards. Avalanche hazard may be solely the result of environmental events such as significant snowfall over a short period of time (e.g. 0.50 m in 24 h), or due the combination of environmental and direct human activity as in the case of recreational avalanche accidents. Both perspectives are macro in scale and problem identification, and do little to add insight into accident avoidance.

In an effort to more closely understand the causes of recreational avalanche accidents, researchers have shifted their emphasis towards a more: "… comprehensive human–environment perspective that also integrates societal and human aspects into the assessment and mitigation of natural hazards, placing considerably more emphasis on social science contributions." (Haegeli et al., 2010, p. 186).

Likewise, for our setting – backcountry avalanche terrain, there has been an asymmetric mix of research focusing on the physical object the activity is based around (i.e. snowpack stability assessment), as evidenced by e.g. Barbolini et al. (2011); Harvey et al. (2002); Schweizer et al. (2020), and the location and timing of events, e.g. Jamieson & Stethem, 2002; Boyd et al., 2009; Spencer and Ashley, 2011; Höller, 2017; Pfeifer et al., 2018, and Techel et al., 2016, with notably less attention given to the human drivers of accidents and associated decision processes (i.e. imperfect decision making, poor communication skills, lack of pre-trip planning etc.).

Over the last decade or more, however, there has been an increasing awareness of the importance of human factors on avalanche safety, and accordingly the number of studies on the human dimension of avalanche safety is steadily growing. The majority of the work is focused on recreationists (e.g. Atkins, 2000; McCammon, 2004; Haegeli et al., 2010; Procter et al., 2013; Zweifel and Haegeli, 2014; Hendrikx & Johnson, 2016a; Hendrikx & Johnson, 2016b; Marengo et al., 2017; Mannberg et al., 2020; Saly et al., 2020; Sykes et al., 2020; Johnson & Hendrikx, 2021), with relatively fewer studies focused on avalanche professionals (e.g. Hendrikx et al., 2016; Johnson et al., 2016; Simenhois and Savage, 2010; Stewart-Patterson, 2014). This work contributes to this stream of research and expands our understanding of the drivers of recreational avalanche accidents through the investigation of decisions by individuals as they negotiate winter backcountry terrain while skiing and riding. We do so through a combination of crowd sourced survey data and GPS tracking.

2.2. GPS tracking, terrain and backcountry users

The work of McCammon (2000; 2002; 2004) and his application of heuristic decision making as it related to avalanche accidents marked an important paradigm shift away from solely snowpack and weather-related causes of accidents to one based on a mix of human factors (i.e. demographics, experience, group dynamics). Of particular significance to this current study is the apparent connection between skier experience and avalanche accidents and a set of decision biases (McCammon, 2002; 2004). However, operationalization of these decision biases has been problematic, and remains elusive (Johnson et al., 2020).

Field level investigations of the decision process have been problematic until the recent widespread use of GPS or other tracking technology. Within the last few years, the ubiquitous use of GPS technology in cell phones and recreational navigation devices has greatly increased the potential for data collection in this setting (e.g. Bielánski et al., 2018; Hendrikx et al., 2016; Hendrikx & Johnson, 2016a; Kliskey, 2000; Olson et al., 2017; Rupf et al., 2011; Sykes et al., 2020; Thumlert and Haegeli, 2018; Winkler et al., 2021).

Prior, initial analysis of these data presented here (Hendrikx & Johnson, 2016a; Johnson & Hendrikx, 2021) only considered the most extreme (or steepest) component of a day – i.e. the 95th, 99th percentiles of the slopes used, to show changes in travel behavior as a function of education and hazard. While this simple metric provided some insights, the metric represents an oversimplification to quantify terrain severity. As such a more integrated and nuanced approach is needed to understand terrain use in avalanche terrain.

One of several alternatives to the use of slope angle alone, is the utilization of a more comprehensive terrain analyses approach (e.g. Harvey et al., 2018, pp. 1625–1631; Schmudlach et al., 2018; Statham et al., 2006). We adopt the Avalanche Terrain Exposure Scale (ATES) rating approach (Statham et al., 2006). ATES is a method to express the severity of avalanche terrain to riders, and is used in North America and parts of Europe (Statham et al., 2006; Gavaldá et al., 2013; Larsen, Hendrikx, et al., 2020; 2020b). The ATES model is divided into two separate components, a public communication model and a technical model. The technical model is used to guide experts using 11 geographic parameters to categorize a route into a public communication model consisting of three classes with increasing avalanche severity; Class 1 "Simple", Class 2 "Challenging", or Class 3 "Complex" (Statham et al., 2006) (Table 1). For more details on the technical model refer to Statham et al. (2006) and how it can be applied spatially refer to Larsen, Hendrikx, et al. (2020).

The main disadvantage of ATES is that it is not currently available for all backcountry avalanche areas around the World, and manual mapping

Table 1
Avalanche Terrain Exposure Scale (ATES) v.1/04. Public communication model (from Statham et al., 2006).

Simple (class 1)	Challenging (class 2)	Complex (class 3)
Exposure to low angle or primarily forested terrain. Some forest openings may involve the runout zones of infrequent avalanches. Many options to reduce or eliminate exposure. No glacier travel.	Exposure to well-defined avalanche paths, starting zones or terrain traps; options exist to reduce or eliminate exposure with careful route-finding. Glacier travel is straightforward but crevasse hazards may exist.	Exposure to multiple overlapping avalanche paths or large expanses of steep, open terrain; multiple avalanche starting zones and terrain traps below; minimal options to reduce exposure. Complicated glacier travel with extensive crevasse bands or icefalls.

is time consuming. Recent work by Larsen et al. (2020a; 2020b) is aiming to resolve this deficiency, but spatial ATES coverage is still limited. Working within a limited geographic area, Sykes et al. (2020) used a combination of intercept survey and GPS tracking to examine decision making in a backcountry area in SW Montana using ATES. This work found that skier gender and formal avalanche education were shown to be important with regards to terrain choice and exposure as quantified using ATES. This study, and others prior, clearly show the value of an integrated and comprehensive human-environment perspective to understanding decision making in this setting.

2.3. Terrain focused paradigm

Ski touring groups rely on their own expertise and group skills to successfully navigate hazardous terrain. While sometimes complex, these small group decisions are typically “self-contained” in terms of responsibility and outcome. Ideally, the decision process is initiated at the planning stage where communication is open to all members; the goal(s) for the day are agreed on; and consideration of the weather, snowpack conditions, and avalanche hazard[1] are assimilated into the group decision with respect to the day’s tour. For backcountry riders the decision of whether or how to navigate potentially avalanche prone terrain may change as these same factors are considered throughout the trip as snowpack conditions or weather changes. Many avalanche accidents are the result of decision-making flaws or bias somewhere in the decision process which leads to inappropriate terrain selection and unfortunate outcomes (e.g. Atkins, 2000; McCammon, 2004; McCammon, 2002; Logan and Atkins, 1996; Johnson et al., 2016).

We focus our approach on the concept that hazardous terrain comprised of complex geographical features, has a quantifiable effect on decision-making by small groups of people traveling or working under conditions of high risk/low probability catastrophic events in natural landscapes. Winkler et al., 2021 used over 2 million GPS points to illustrate a method to quantify this risk. Our theory, grounded in geospatial thought, is that geographic constraints may be the primary decision-making driver for such high-stakes decisions and act as the instigating factor for decision making. The presence of spatially distributed geographic and topographic features or conditions (snowpack, weather) instigates the need for a decision(s) throughout the duration of an excursion. Encountering potential hazard elements provides the impetus for social interaction among the group. As such, the geographic location of these potential hazard elements plays the key role in the initiation of the subsequent decision-making process. While the physical setting prompts the decision-making process, it is the group dynamic and respective behaviors that ultimately influence the outcome of how the group manages the obstacle, terrain or hazard. These features are central to the naturalistic decision-making (NDM) paradigm where real world constraints and incomplete information heavily influence decisions (Zsambok and Klein, 1997; Todd and Gigerenzer, 2001; McLennan et al., 2006). For this reason, we focus on the spatial location of the activity, and the terrain metrics we can extract, and then consider the combined group dynamics and demographic elements that lead to the decision-making outcome.

Similar methods and frameworks have been used to examine, among other issues, conflict between different users, where geographic complexity, terrain and user preferences are critical. This includes related work in winter recreation by Miller et al. (2017) examining the impact of zoning for winter recreation, Kliskey (2000) and Albritton and Stein (2011) to understand motorized and non-motorized users, and more broadly for other recreational opportunities (Brabyn & Sutton, 2013).

We elect to use the ATES framework as our measure of risk, as it is spatially explicit and recognizes such constraints as avalanche paths; large expanses of steep, open terrain; and terrain traps. Therefore, by examining the terrain that is used, we can infer decision making outcomes, and using ATES are able to assess risk by different groups as they negotiate terrain.

This research will expand our understanding of how terrain influences decision-making by small groups of people traveling or working under conditions of high risk/low probability catastrophic events in natural landscapes. We propose the intersections of geography, demographics, experience, and behavior data expands our current insights into the causes of avalanche accidents. Accordingly, this paper focuses on the following questions:

1. How do backcountry users make decisions in backcountry terrain?
2. What type of backcountry terrain do they use, as quantified using simple terrain metrics and ATES? And does this change due to user experience and posted avalanche hazard?
3. Do they alter their backcountry terrain use based on group factors?

By improving our understanding of these issues, we aim to provide insights on the groups and situations where backcountry users may be exposed to increased risk from avalanche in complex terrain.

3. Methods

3.1. Data collection

Our data collection methods are fully documented in Johnson and Hendrikx (2021), so will only be briefly described here. Participants completed a pre-season survey that described their demographics (gender, age, education, employment status, marital status, children), skill level in several areas (other outdoor activities, years of skiing, ski/board expertise from beginner to expert), backcountry skills (terrain and snowpack assessment proficiency, avalanche education, avalanche transceiver proficiency) and personal decision-making strategies. After this initial survey, they were asked to record GPS tracks via a smartphone application and submit it to the project email address (tracks@montana.edu). Finally, an automated reply sent them an additional survey that queried their day’s traveling companions’ demographics, decision making routine, and several questions that measured the decision process. These three layers of data, the initial pre-trip survey, a post-trip surveys and the GPS track, represents a fully completed dataset for each respondent. Respondents were able to submit more than one track

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[1] Avalanche hazard is a semi-quantitative framework used by avalanche forecasters to denote the likelihood for avalanches to cause harm or injury to backcountry travelers. Avalanche hazard is defined as a potentially damaging process resulting from a mass of falling snow rapidly down a mountain side. The avalanche hazard commonly is indicated by standardized danger levels which are applied in many alpine countries. The North American Avalanche Danger Scale describes the chance of an avalanche occurring and how big/destructive it will be (Statham et al., 2018). A copy of the scale is presented in Appendix 1.

and post trip survey.

Our sampling was based on a modified snowball convenience strategy. We depended on exposure to the project via public talks, articles in relevant press, notices on avalanche advisory sites, electronic list servers of associations and memberships, and word of mouth to solicit respondents for the pre-season survey. Our surveys have undergone several iterations and appear to have a high level of face and test validity (Hendrikx & Johnson, 2016a; Johnson and Hendrikx (2021). A copy of our pre-trip survey, and post-trip survey are available in Johnson and Hendrikx (2021), as supplementary materials.

3.2. Data processing

Submitted tracks were processed in two steps. First, the tracks were converted into an ESRI shapefile and overlaid on a 10m DEM and topographic map. This allowed for rapid manual verification of tracks, and removal of unintended recordings (e.g. leaving the GPS tracking function running when driving home). After checking and trimming of GPS tracks as needed, we then extracted relevant terrain parameters in Google Earth Engine (GEE) (Gorelick et al., 2017). For each track, with the use of a 10 m DEM, at every GPS point, we extracted; slope (min/mean/max and percentiles), and aspect, and Avalanche Terrain Exposure Scale (ATES) rating. Our ATES layer was produced using the workflow as presented in Larsen et al. (2020a). This workflow has produced ATES mapping for all avalanche regions in Norway, and also for selected avalanche regions in the USA and Canada. In an approach similar to Sykes et al. (2020), to utilize the ATES mapping in our analysis, we calculated the total distance, and percentage of track distance in and out of ATES terrain, and each ATES class. We also calculate the total amount of time in ATES terrain, and ATES class 3 (i.e. complex) terrain for each track (Fig. 1).

We consider the ATES class 3 terrain as the most hazardous component of each track, and the percentage of track, and critically the time (in minutes) in ATES terrain analysis represents our key metrics of risk from avalanches. This is based on the theory that the probability of involvement with an avalanche is higher, and the consequences of that involvement are higher when traveling a longer distance, and a longer time, in ATES class 3, complex terrain. This approach of using time is also consistent with other methods of risk assessment (e.g. calculating a fatal accident rate (FAR) where number of observed fatalities are considered in terms of total exposure hours to a given risk), and the Avalanche Hazard Index (AHI) where the time exposed to avalanche hazards, and the time stationary in avalanche paths is critically important (Schaerer, 1989; Hendrikx & Owens, 2008). We also calculated travel speed, total distance and total time of travel. Finally, we note that time in avalanche terrain, and specifically ATES class 3 terrain is correlated with distance in avalanche terrain and percentage of track in ATES (Appendix 2C), but for the reasons noted above consider that time is more critical metric for our analysis moving forward.

3.3. Data analysis

For analysis of the terrain metrics, the Likert scale responses, and other survey responses for two independent samples we used the Mann-Whitney *U* Test, with significance at the $p < 0.05$ level. For multiple independent samples (i.e. more than two groups) we used the non-parametric Kruskal-Wallis Test, with significance at the $p < 0.05$ level.

In addition to these tests, a General Regression Tree (GRT) model (Breiman et al., 1993), was used to explain the continuous variable of percentage of complex terrain used from a set of continuous variables and categorical predictor variables. The application of classification and regression trees have been applied to numerous studies, including avalanche and terrain related (e.g. Hendrikx et al., 2005; Hendrikx et al., 2014; Peitzsch et al., 2015).

This technique was used as it provides a clearer and often more easily understood interpretations of complex interactions than other model

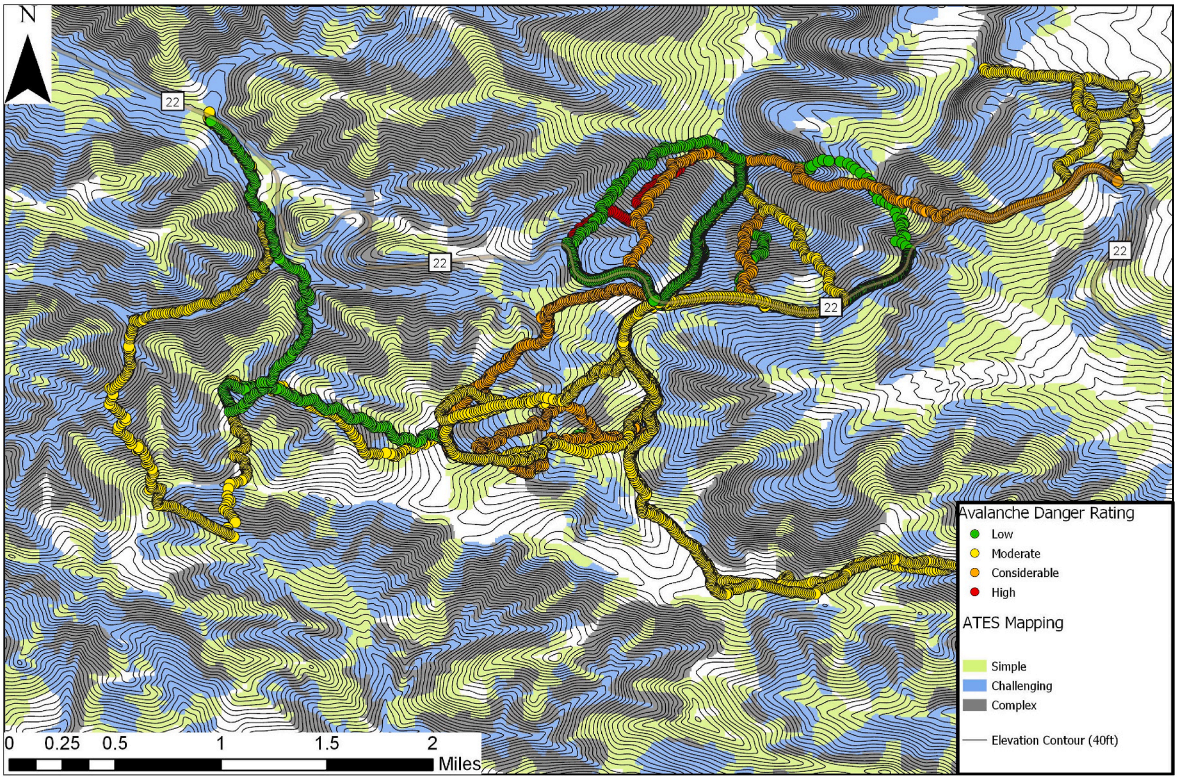

Fig. 1. An example of GPS recorded backcountry ski tracks from Teton Pass, Wyoming, showing multiple tracks from different days, overlaid on our ATES mapping. The complex terrain is marked in black, challenging terrain in blue, and simple terrain in green. White represents non-ATES terrain. The tracks are color coded based on the regional avalanche advisory for the given day of travel.

constructions (Davis et al., 1999; Hendrikx et al., 2014), which makes them ideal for understanding real-world decision making. A full discussion of classification and regression trees is given by Breiman et al. (1993, p. 358). Advances in regression tree techniques like bagging predictors (Breiman, 1996) and random forests (Breiman, 2001) were not considered due to their added complexity, which then negates some of these earlier noted advantages.

We selected variables for our model that were shown to be significant ($p < 0.05$), or marginally significant ($p < 0.10$) in the Mann-Whitney U or Kruskal-Wallis test results. We used both node variance and minimum node member number as our key stopping criteria.

Similar to the approach of Hendrikx et al. (2014), we initially permitted the tree to continue to grow, i.e. an over-fitted tree. We then employed a 10-fold cross validation technique, to reduce the tree to a more statistically defensible level for predictive purposes and ensure that splits were not due to random noise. The technique is described by Breiman et al. (1993, p. 358) and has been employed by Hendrikx et al. (2005), Baggi and Schweizer (2009), Hendrikx et al. (2014) and Peitzsch et al. (2015), for avalanche related research.

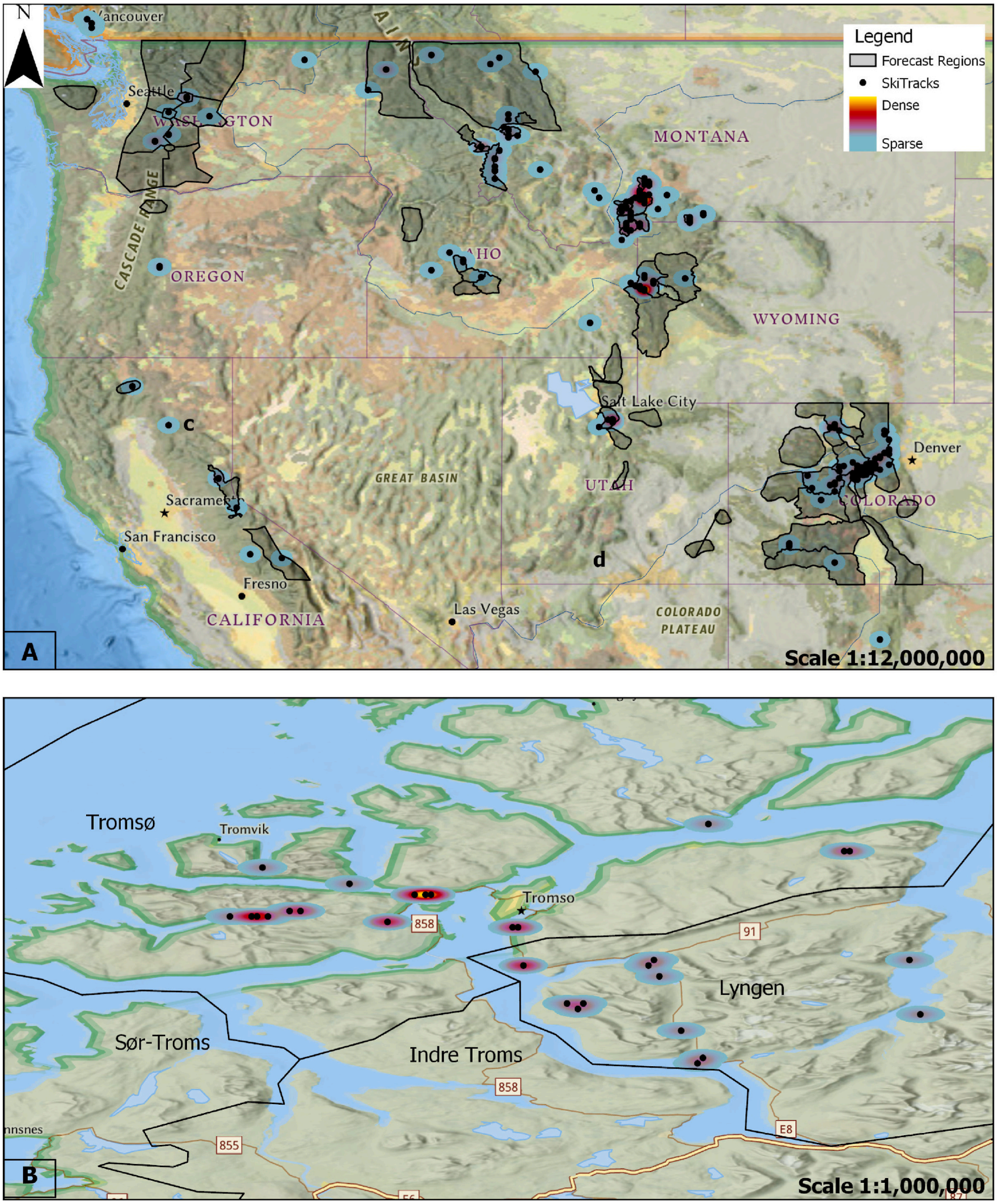

Fig. 2. Map showing the distribution of our track data, which were focused in the conterminous United States, and northern Norway. Heatmap symbology is in reference to the relative density of submitted GPS track data, where more tracks in one area represents higher density.

4. Results and discussion

4.1. Overview of sample data

At the end of the main data collection period, (i.e. the northern hemisphere 2016–17 winter season), we had enrolled more than 2000 unique participants from 12 US states and Canadian provinces, and 6 alpine countries in Europe. However, the final number of individuals that fully participated in our study and provide us with; (1) a completed preseason survey; (2) a GPS track, and; (3) a completed post-trip survey was much lower (n = 482). After cleaning the data set for missing data, incompatible data formats, and other GPS data issues, we acquired a total sample of 770 GPS tracks, representing almost 1.3 million GPS data points, with associated and completed pre- and post-surveys from these 482 unique participants. On average, this represented 1.6 tracks per unique participant. The number of tracks provided however was not equal across all participants, with a little over 41% of participants providing only one track, 25% providing 2 tracks, 8% proving 3 tracks, 11% providing between 4 and 5 tracks, and 15% providing more than 5 tracks. Participants that provided the more than 5 tracks all self-identified as experts, and review of their data suggested that these tracks were from trips under a range of avalanche and group situations. Fig. 2 presents a summary of the spatial distribution of our tracks, which were located in the conterminous United States, and northern Norway. This represents more than 80% of our total data set. The respective avalanche forecast area polygons are also shown. A narrative summary of these data is presented in Johnson and Hendrikx (2021), and the summary statistics are presented below (Table 2).

Our demographic results mirror closely other examinations of participants in the sport of backcountry skiing and riding (Bright, 2010; Procter et al., 2013). However, we did have fewer female participants than Mannberg et al. (2018; 2020), who proactively recruited females via several online discussion groups and social media, and Greene et al. (2022) that focused on introductory courses. Our sample is also slightly more skewed towards self-identified experts and intermediates, with very few novices. This is likely a reflection of our sampling and methodology and multi-step data collection process to obtain a complete record (see Johnson & Hendrikx, 2021 for a full discussion of the sampling methodology).

Based on the above, a typical survey participant was a male, aged 26–35, has a university degree, is employed full time working 40 or more hours per week, has no children, and participated in several outdoor sports with hiking, downhill skiing, camping and mountain biking, trail running and rock climbing being done by 50% or more of the participants. In most respects our sample closely mirrors findings by the Outdoor Industry Association (2020) and the Canadian Tourism Commission (2000), and to a lesser extent the survey results of the professional avalanche community (Johnson et al., 2016).

Table 2
Summary of participant responses that provided complete data sets.

Variable	Responses (N)		
Age	482	35.6 years (Mean)	12.2 years (std. dev.)
Gender	482	435 Male	47 Female
Education	480	72 non-degree	408 Degree or Graduate degree
Marital status	482	288 Single	212 married or other
Children <18 in house	482	415 no children	67, ≥1 child
Employment	433	251 Full time	182 Part time, Student or Retired
Experience	433	301 Expert	121 Intermediate, 11 Novice
Other sports	482	5.5 count (Mean)	1.9 count (std. dev.)

One of our key questions focused on self-identified backcountry skiing experience level (“Which of the following statements most closely describe your experience as a backcountry (BC) skier?“), with 62% self-identified as experts (n = 301), 25% as intermediates (n = 121) and only 2% (n = 11) as novice. Our pre-trip survey provided the following descriptions to aid self-identification:

> **Novice:** I am a Novice with little to no experience with winter backcountry travel, little to no formal avalanche education, no consistent mentor or group leader.
> **Intermediate:** I am an Intermediate with a Level One avalanche course (or equivalent) and/or few years (i.e. <5 yrs) backcountry experience.
> **Expert:** I am an Expert with Level One/Two avalanche education course, and/or many, (i.e. > 5 yrs) backcountry experience, and/or professional experience in industry that requires me to be proficient. This skier is a frequent group leader and/or trip initiator.

However, self-assessment of backcountry skiing skills is an imprecise measure, so we attempted to independently assess proficiency using several additional questions including level of avalanche education, and questions that queried respondents' self-evaluated skills, e.g., skills with an avalanche transceiver, their backcountry terrain and snow management skills, and years of backcountry skiing experience (Table 3).

Our statistical analyses (Mann-Whitney U test, $p < 0.05$) show that self-assessed expert backcountry skiers rate themselves as significantly more skilled than self-assessed intermediate skiers on all these skill questions in Table 3, and also had higher levels of avalanche education. As can be seen in Appendix 2A, the differences are very consistent across the different measures. Therefore, to simplify the presentation of our main results and analysis of terrain used, we use the three categories of self-assessed backcountry skiing skills (novice, intermediate, expert) as a robust indicator of overall self-assessed skills in our analysis.

4.2. How do backcountry users of different skill levels make decisions in backcountry terrain?

Avalanche terrain use decision making processes are known to vary as a function of avalanche education and experience (Landrø et al., 2020). Based on the clear difference between intermediate and experts with regards to their self-assessed fundamental skills (as detailed in section 4.1), we also tested to see if there was a difference in their decision-making processes. To assess this component, we used a series of questions that focused on the decision-making process by the group. These questions are summarized in Table 4.

Of these 14 decision making questions in our post-trip, only three showed statistically significant differences in response, between intermediate and expert groups using the Mann-Whitney U Test at the $p < 0.05$ level (Appendix 2B).

These results indicate that self-identified experts recognize the value of a well-structured and communicated plan, and are more likely to employ such a process to define the real issues before going on tour.

In addition to communication, we aligned several of our questions to investigate the presence of decision bias as described by McCammon (2000; 2002; 2004). We observe no significant difference between groups for these questions. This does not suggest that both groups are, or are not susceptible to these heuristic traps, but rather that in our data, experience does not influence the susceptibility to them. These results contrast with those presented by McCammon. Table 5 presents our comparisons. However, it should be noted that McCammon's decision heuristics and biases are poorly operationalized and there are no agreed upon conventions for doing so (Johnson et al., 2020).

Table 3
Summary of pre-trip survey questions related to snowpack, terrain, transceiver, backcountry skill level and avalanche education level. Median scores are shown for intermediate and experts. All questions were found to have significant difference ($p < 0.05$ level) between experts and intermediates.

Variable	Question	Scale	Intermediate (median)	Expert (median)
Snowpack Assessment	Please select the statement below that most closely describes your snowpack assessment skills while backcountry skiing/riding	4 point scale	5 (Moderate Confidence)	3 (High Confidence)
Terrain Management Ability	Please select the statement below that most closely describes your terrain management skills while skiing/riding	5 point scale	3 (High Confidence)	4 (Highly Proficient)
Transceiver competency	Please select the statement that most closely fits your skill level with your avalanche transceiver	5 point scale	4 (Very Proficient)	5 (Extremely Proficient)
BC Skill level	Rating systems designed for ski schools at ski resorts are not always appropriate in representing the skills and comfort level necessary for skiing/riding in a remote, wilderness environment. Even though we may feel proficient at the lift-served ski area, we recognize that different skills and skiing abilities apply in the backcountry in high alpine avalanche terrain. Please read the descriptions below and select the one that most closely describes your skill level with respect to you backcountry skills	5 point scale	3 (Level III)	4 (Level IV
BC Skiing Terrain	Please select the statement below that most closely describes your terrain management skills while backcountry skiing/riding	5 point scale	3 (High Confidence)	4 (Highly Proficient)
Avalanche Education	Which of the following formal avalanche training opportunities have you completed?	7 point scale	3 (Level 1)	4 (Level 2)

Table 4
Summary of post-trip survey questions related to snowpack, terrain, transceiver, backcountry skill level and avalanche education level. Those marked in **bold** were found to have significant difference ($p < 0.05$ level) between experts and intermediates. All questions used a 7-point scale. Median scores are shown for intermediate and experts.

Q #	Question	Intermediate (median)	Expert (median)
Q1.	Getting “first tracks” in powder is an important part of backcountry skiing	3 (Occasionally)	4 (Sometimes)
Q2.	When backcountry skiing I identify a goal and try to achieve it	5 (Frequently)	5 (Frequently)
Q3.	If I see others have successfully skied a slope, I tend to use their behavior as an indicator of avalanche hazard	2 (Rarely)	3 (Occasionally)
Q4.	When I ski a place familiar to me I tend to depend on past experiences to predict hazards	2 (Rarely)	2 (Rarely)
Q5.	I emphasize how confident I am in my decision as a way to gain support for my plans	3 (Occasionally)	2 (Rarely)
Q6.	I prefer to make decisions on my own, and then let other people know what I’ve decided	5 (Frequently)	5 (Frequently)
Q7.	Some of the options I’ve chosen have been much more difficult to implement than I had expected	3 (Occasionally)	3 (Occasionally)
Q8.	When communicating my decision, I include my rationale and justification	5 (Frequently)	6 (V. Frequently)
Q9.	In a group decision making process, I tend to support my friends’ proposals and try to find a way to make them work	5 (Frequently)	5 (Frequently)
Q10.	**Before I communicate my decision, I create an implementation plan**	**4 (Sometimes)**	**7 (Always)**
Q11.	**I use a well-defined process to structure my decisions**	**4 (Sometimes)**	**6 (V. Frequently)**
Q12.	I am sometimes surprised by the consequences of my decisions	2 (Rarely)	2 (Rarely)
Q13.	**I try to determine the real issue before starting a decision-making process**	**4 (Sometimes)**	**6 (V. Frequently)**
Q14.	I evaluate the risks associated with each alternative before making a decision	5 (Frequently)	6 (V. Frequently)

Table 5
Decision making questions as compared to McCammon heuristics.

Our questions	McCammon Decision Biases (2002)
Q1. Getting “first tracks” in powder is an important part of backcountry skiing.	**First tracks.** This refers to scarcity, the tendency to value resources or opportunities in proportion to the chance that you may lose them. For backcountry skiers, wanting to ski untouched powder adds to the excitement and so skiers may ignore avalanche warning signs.
Q2. When backcountry skiing I identify a goal and try to achieve it.	**Consistency**—an initial decision about something, subsequent decisions are much easier if we maintain consistency with previous decisions. i.e. …. We’re determined to ski this slope no matter what …
Q3. If I see others have successfully skied a slope, I tend to use their behavior as an indicator of avalanche danger.	**Social Facilitation** presence of other people enhances risk-taking by a subject. Fresh tracks on the slope encourage one toward safe conditions even through avalanche danger rating is high.
Q4. When I ski a place familiar to me I tend to depend on past experiences to predict avalanche danger	**Familiarity**—our past actions to guide our behavior in a familiar setting. You’ve skied this slope a dozen times and it’s never slid, so despite obvious avalanche warning signs, you ski it again this time.

4.3. *What type of backcountry terrain do they use? And the role of experience and avalanche danger ratings*

In this section, we examine if self-assessed backcountry skills influences terrain choices, and if these choices are affected by the level of avalanche danger. Our sample of 770 tracks, represents over 6400 km of backcountry travel in a range of different geographic areas, snow climates and under a range of avalanche conditions. Across the entire data set, the median trip length in our sample was 9.1 km (with novices skiing the least distance), and the median duration was 234 min (with novices skiing the shortest duration).

When we consider the role of experience in terms of resulting terrain use, we observe that there is a significant difference ($p < 0.05$) between intermediate and expert groups. Specifically, we observe that simple terrain metrics using slope, including the minimum and maximum slope angle, 90th, 95th and 99th percentile of slope angles show differences, with higher median values for experts relative to intermediates. We also observe a difference in terms of the percentage of track in all ATES classes (where class 1 is simple terrain, class 2 is challenging terrain, and class 3 is complex terrain). In terms of total time spent in ATES terrain in general, and class 3 (i.e. complex) ATES terrain (Fig. 3a, Table 6),

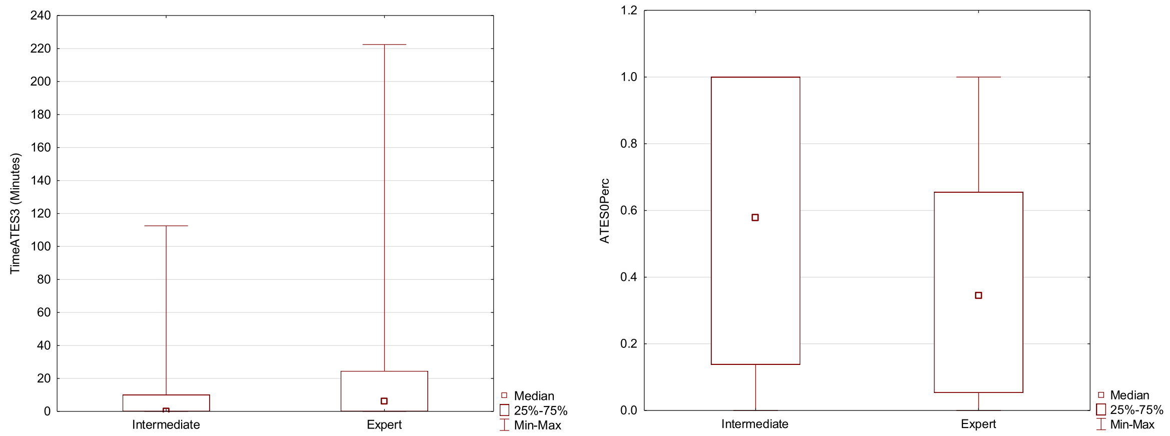

Fig. 3. Box and whisker plots with the minimum, maximum, median and 25–75% range for; (A) Time in ATES class 3 terrain (TimeATES3) in minutes, intermediate vs expert, and; (B) Percentage of track in non-ATES terrain (ATES0Perc), intermediate ($n = 121$) vs expert ($n = 301$). Medians and p-values are in Table 6.

Table 6

Mann-Whitney *U* Test (with continuity correction) with tests significant at the $p < 0.05$ level results shown in **bold**. Intermediate ($n = 121$) vs Expert ($n = 301$).

Variable	Definition	p-value	Intermediate (median)	Expert (median)
minslope	Minimum slope angle in degrees	0.014	1.39	1.65
maxslope	Maximum slope angle in degrees	0.019	40.59	42.72
meanslope	Mean slope angle in degrees	0.072	16.10	17.18
50th slope angle	50th percentile slope angle in degrees	0.246	15.70	16.55
90th slope angle	**90th percentile slope angle in degrees**	**0.006**	**25.98**	**27.89**
95th slope angle	**95th percentile slope angle in degrees**	**0.011**	**29.70**	**30.99**
99th slope angle	**99th percentile slope angle in degrees**	**0.005**	**34.43**	**36.66**
ATES0Perc	**Percentage in non-ATES terrain**	**0.000**	**0.60**	**0.38**
ATES1Perc	**Percentage in Simple ATES terrain**	**0.000**	**0.19**	**0.28**
ATES2Perc	**Percentage in Challenging ATES terrain**	**0.001**	**0.17**	**0.26**
ATES3Perc	**Percentage in Complex ATES terrain**	**0.000**	**0.04**	**0.08**
TimeInATES	**Time in any ATES terrain (minutes)**	**0.000**	**55.85**	**117.34**
TimeATES3	**Time in Complex ATES terrain (minutes)**	**0.000**	**0.04**	**8.74**

experts had a higher median time exposed. Only the percentage of track not in ATES terrain (ATES0Perc) was greater for intermediates (60%) vs experts (38%), which is consistent with the increase for the other ATES metrics for experts (Fig. 3b, Table 6). We also note that some of these parameters are highly correlated with one another, e.g. time in ATES class 3 terrain and percentage of track in ATES class 3 terrain. A correlation matrix showing the relationship between the slope percentiles, percentage of track in ATES terrain and time in ATES terrain is presented in Appendix 2C.

While indices of slope angles, and ATES terrain are a proxy for the terrain exposure to avalanches for intermediates and experts, it does not necessarily correlate directly to their risk. The experts, while clearly traveling more in exposed terrain, and spending longer periods of time in avalanche terrain, may only be doing so under lower avalanche danger ratings. Accordingly, we now examine the relationship between avalanche danger rating, BC experience, and terrain use.

Of the 770 tracks, 555 trips were logged within a backcountry avalanche advisory area, with 474 trips during a period of time with a posted avalanche danger rating (i.e. low, moderate, considerable, high). Table 7 (left side) presents a summary of the posted avalanche danger rating for all trips with an advisory, with the most trips under moderate danger ratings (50%, $n = 238$), followed by considerable avalanche danger ratings (28%, $n = 133$). Eighteen percent of trips ($n = 87$) were undertaken during low avalanche danger ratings, and only 3% of the trips ($n = 16$) were undertaken during a high avalanche danger rating.

When we further sub-divide these trips, as a function of backcountry experience under posted avalanche danger ratings (Table 7, right side), we see an insignificant shift in the percentage of trips as a function of the intermediate and expert user groups. The novice user group shows marked differences when compared to the other groups, but we have little confidence in these findings for novices, due to the very small sample size.

The percentage of trips for experts (30%) and intermediates (32%), relative to all trips, under considerable and high avalanche danger ratings were similar for intermediates and experts. These two analyses in combination show that expert travelers use more exposed terrain and spend longer periods of time in exposed terrain across a similar distribution of avalanche danger rating as intermediates. Fig. 4 illustrates this for expert vs intermediate travelers, across all four avalanche danger ratings, as plotted against time in class 3 ATES terrain. The percentage of track in ATES terrain, and percentage in class 3 ATES terrain show similar patterns.

The results suggest that experienced users (Experts) in our sample did have increased exposure to more serious avalanche terrain, as represented by the time in class 3 ATES terrain (but also for percentage of track in challenging terrain), across all but high avalanche ratings. It is unknown why intermediate users have a higher upper quartile range for High hazard conditions, but given the small number of trips ($n = 13$)

Table 7

Avalanche danger rating for all trips with ratings ($n = 474$), and for all trips with ratings and BC experience ($n = 345$) (both count and percentage are shown).

Danger rating	All		Novice		Intermediate		Expert	
Low	87	18%	3	38%	22	24%	43	18%
Moderate	238	50%	1	13%	41	44%	127	52%
Considerable	133	28%	4	50%	27	29%	64	26%
High	16	3%	0	0%	3	3%	10	4%
Grand Total	474	100%	8	100%	93	100%	244	100%

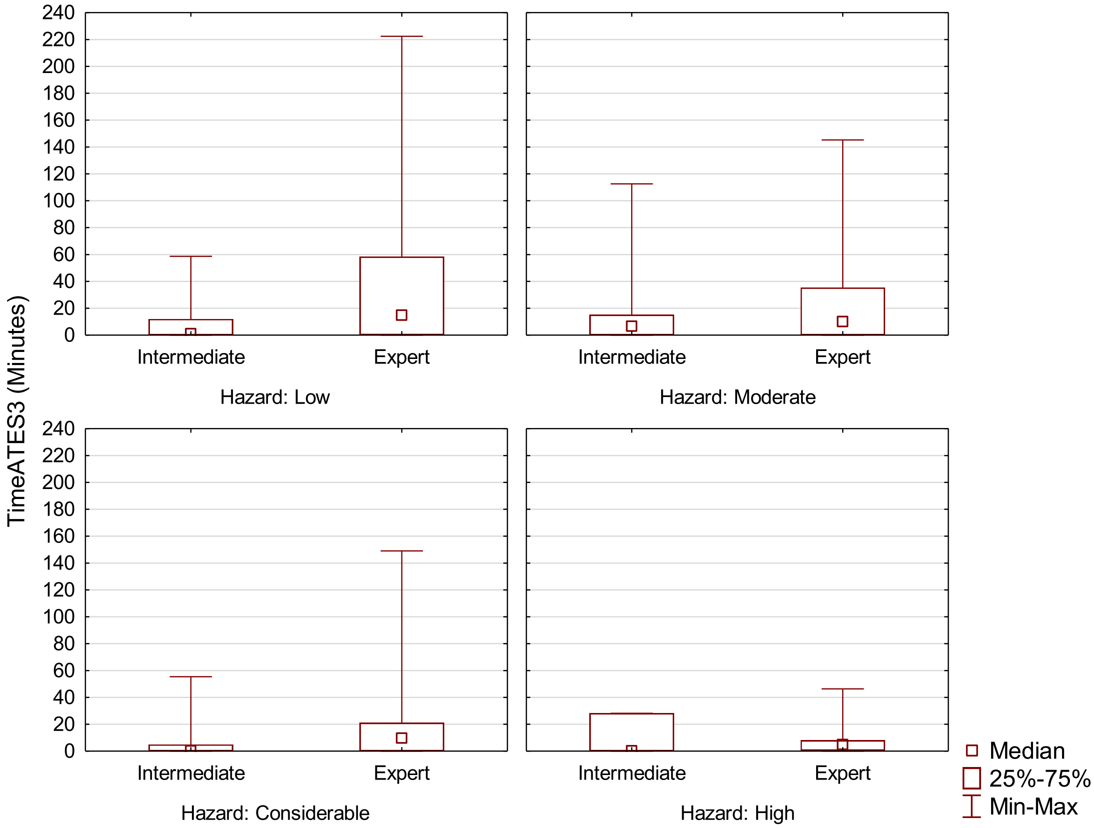

Fig. 4. Box and whisker plots with the minimum, maximum, median and 25–75% range for time in complex terrain (TimeATES3) in minutes as a function of the posted backcountry avalanche danger rating and grouped by BC experience, for; Low (n = 65); Moderate (n = 168); Considerable (n = 91); High (n = 13).

under High, these differences may simply be due to chance, or could reflect difference due to the avalanche problem (which we did not examine), but are unlikely to be representative of broader use patterns.

Prior work considering age (Peitzsch et al., 2020) and experience (McCammon 2002) has shown these factors to be important determinates of accidents. By contrast, the work by Winkler et al. (2016), using an extensive data set based on the Swiss Federal Office of statistics, showed a higher risk for younger cohorts (including snow shoe users and skiers). Our sample of non-accident trips is consistent with the accident data, and shows that experience, which is highly correlated to

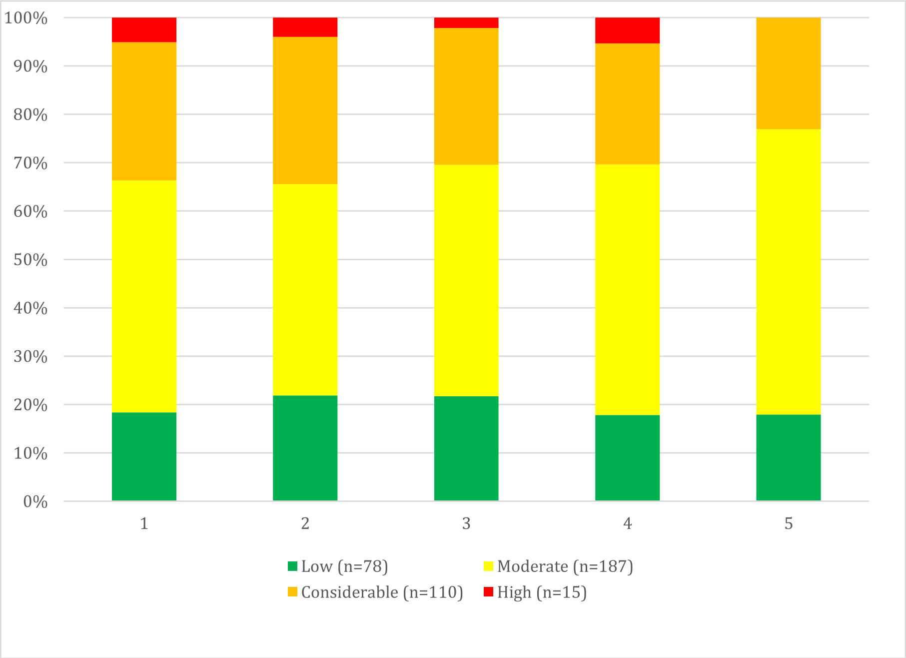

Fig. 5. Proportion of trips, as a function of group size, and coded by avalanche danger rating (n = 390 trips). Count of trips for each avalanche danger level is shown.

age, is correlated with increased use of more serious backcountry avalanche terrain under most avalanche danger ratings.

4.4. Backcountry terrain use and group factors

4.4.1. Group size

Our sample of 770 tracks reported group size for 428 tracks, representing over 1050 individuals. Groups of two travelers were the most common travel group size with 40% ($n = 170$) of all reported trips involving two members. Solo travel, while widely regarded as more risky behavior in avalanche terrain represented more than 24% ($n = 104$) of all reported trips. Most of these solo trips were undertaken by males, with only 6% being females. Of the solo tracks analyzed, almost two thirds included traveling in complex terrain as defined by ATES. Large groups, with 5 or more people, represented just under 10% of our sample. Our data is similar to Zweifel et al. (2016) who also reported a median group size of 2, and few larger groups.

When we compare group size as a function of posted avalanche danger rating ($n = 390$) (Fig. 5), we do not observe a significant difference in the group size. There are similar proportions of group sizes from 1 to 4 under low, moderate and considerable avalanche danger ratings. While not meeting our requirements for statistically significance, it is worth noting that there were no trips reported by groups of 5 or more under high avalanche danger rating. Large groups have been shown to have increased risk (Zweifel et al., 2016), so this absence of groups of 5 or more under high avalanche danger ratings is encouraging, but again we do note the small number of days documented with a high danger rating. Solo travel occurred under all avalanche danger ratings, including 5 trips under high avalanche danger rating.

When we examine the percentage of the track in complex terrain as a function of the posted avalanche danger rating by group size (Fig. 6) we see that, under low avalanche danger rating, larger groups (5 or more), spent less time in complex terrain and that they were statistically significantly different ($p < 0.05$) than all other groups.[2] We also see that groups of 2 under high avalanche danger rating were marginally significantly different than all other groups, spending more time in complex terrain. Note that in both of these cases, the count of trips was very low ($n = 7$ and $n = 6$ respectively), so we have limited confidence in these differences despite the statistical result. No other significant differences were noted, as a function of group size when categorized by avalanche danger rating. These differences were also noted when we used percentage of track in complex terrain as our dependent variable.

4.4.2. Group composition

Another group factor of interest, which may influence decision making and resulting terrain use is the gender composition of the group. When considering only groups of two, those comprised of only males were the dominant group composition (27%, $n = 115$), only females represented 1% ($n = 3$), and mixed gender groups of two made up 12% ($n = 50$). Solo males made up the second largest group with 24% ($n = 101$) of the trips.

These groups travelled under a range of avalanche conditions, and groups of two and three males spent statistically more time in complex avalanche terrain than all of the other groups considered. Interestingly, solo males and mixed groups spent similar amounts of time in complex avalanche terrain, and solo females avoided all complex terrain ($n = 3$). We did not test for difference in travel patterns as a function of group composition and avalanche danger rating due to the small sample sizes when placed into these categories.

4.4.3. Other factors

When we look at the groups that were very familiar, or familiar with their ski partner ($n = 231$) vs those that were either skiing alone or had just met their ski partner we see a significant difference in the percentage of complex terrain used ($n = 114$)Those who were most familiar with their partner(s) spent more time in complex terrain (median = 8.3%) than those that were not (median = 4.8%). This makes intuitive sense because familiarity with a partner likely improves the communication needed to travel in more exposed terrain and trust in the event of an avalanche incident is likely higher among those who tour with the same people more frequently.

As part of the daily post-trip survey, we also considered other group-related decision-making factors related to leadership and team dynamics for a subset of our data (seasons 2014–15). In these data, no statistically significant differences emerged with respect to the terrain used for these questions. The same null result was found when we examined the questions in Table 5 related to McCammon decision biases.

Furthermore, questions that related to travel practices, method and frequency of snowpack observations, showed the same, null result with respect to the amount of time in complex terrain, or percentage of track in complex terrain.

The lack of meaningful results for these questions are potentially due to the relatively high level of avalanche education for respondents. These questions reflect the implementation of best practice for safe backcountry travel and may demonstrate the effectiveness of education efforts.

4.5. General Regression Tree (GRT) analysis

Finally, we trained a General Regression Tree (GRT) to explain our continuous variable of time in complex terrain for a given track, from our set of significant ($p < 0.05$) and marginally significant ($p < 0.10$) continuous variables and categorical predictor variables. Due to sporadic missing data and case-wise deletion of events, our final analysis data set was reduced from 770 to 317 tracks. Using this reduced data set, a regression tree was permitted to grow using recursive binary splitting, with the goal to minimize the Residual sum of squares (RSS). At each split, the algorithm continues to search for the split that optimize the RSS at that node. This process was permitted to continue until our stopping criterion was reached (no node contains more than 5% of the total data set, or the RSS decreased less than 1%). Given that our ultimate goal is to understand and potentially predict patterns of terrain use by specific cohorts, rather than just fully describe our data (Shmueli, 2010), we used 10-fold cross validation to prune our over-fit tree to a more defensible level and ensure that splits were not due to random noise.

Fig. 7 shows the resulting tree structure. The first split is based on the self-identified level of backcountry experience and shows that experts (left branch) tend to spend more time in complex terrain (median 24 min) than intermediate and novices (right branch) (median 8 min). Node #2 then splits these experts as a function of their age, where those that are 25 or younger (left branch) tend to spend more time in complex terrain (median 36 min), and those older than 25, are spending less time in complex terrain (median 19 min). Node #5 then splits this group as a function of the group size, where solo groups (left branch) tend to spend less time in complex terrain (median 8 min), and those with two or more members in a group, are spending more time in complex terrain (median 23 min). Finally, this group (Node #7) is then split as a function of the posted backcountry avalanche danger rating, where the trips on high danger rating days (left branch) tend to spend less time in complex terrain (median 13 min), and those trips on all other days, are using more complex terrain (median 26 min). Note that the median trip time for all trips was 234 min. The predictor importance for the parameters used in the tree were; Age (1.0), Avalanche Danger Rating (0.86), Experience (0.63), and Group size (0.53). Note that predictor importance ranking is not the same as the order of the splits in the presented tree, as the predictor importance is a sensitivity parameter, based on reduction in variance (Breiman et al., 1993), and does not necessarily

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[2] Due to small sample sizes, we grouped all groups with between 5 and 10 members in the 5 or more category.

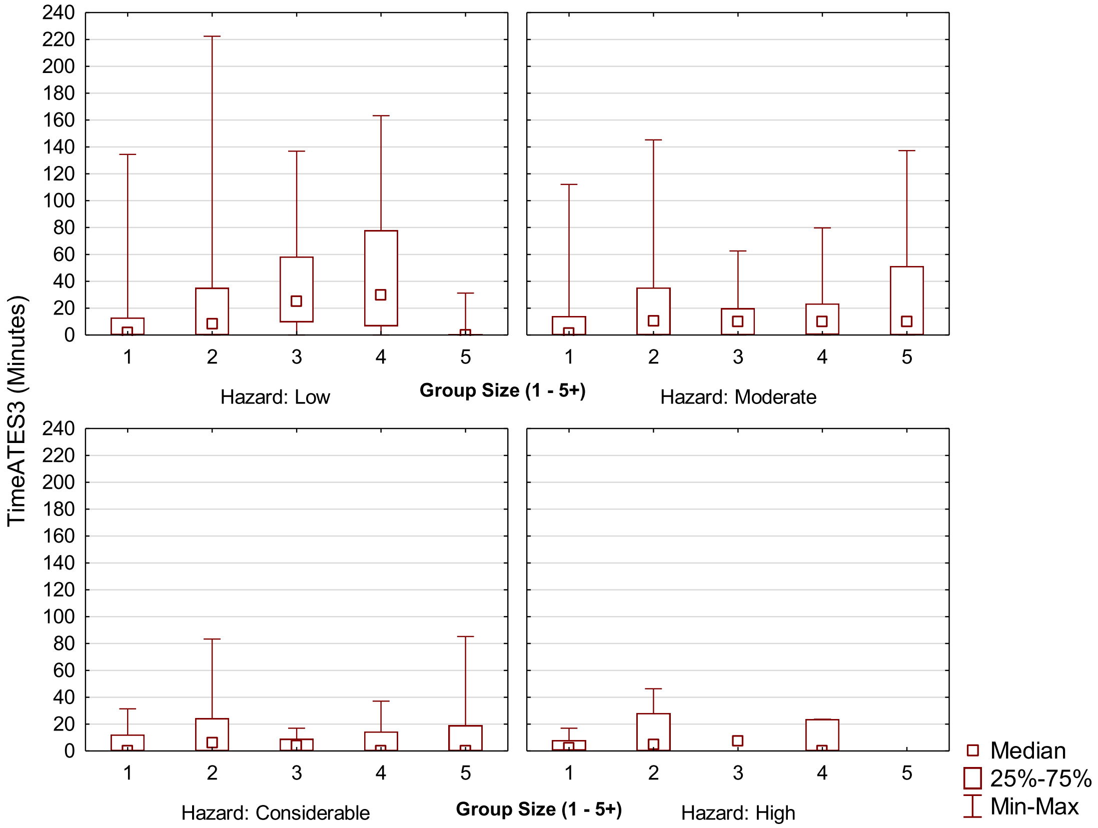

Fig. 6. Box and whisker plots with the minimum, maximum, median and 25–75% range for time in complex terrain (TimeATES3) in minutes as a function of the posted backcountry avalanche danger rating and grouped by group size, where 5 = groups of 5 or more. Note very small sample sizes under High avalanche danger rating for; Low (n = 64); Moderate (n = 168); Considerable (n = 90); High (n = 13).

predict the order of the splits in the cross validated tree.

These splits, the order of these splits, and the parameter importance ranking provide additional insight beyond the univariate analysis presented in the sections above. The first split (on experience level), while one of the lower ratings for parameter importance, aligns well with our prior analysis, where experts are shown to spend more time in complex terrain. This is consistent with the application of years of experience and higher levels of avalanche education and should not necessarily be interpreted to mean that expert skiers are more risk-seeking. Rather, they are applying skills learned over many seasons and in formal avalanche education training.

Interestingly, while age has the highest predictor importance, it is not used until the second split in our final tree. The nature of this split, and location of this split indicates that while important for determining the time spent in complex terrain, it has the most utility for discriminating between experts. The third split, based on group size also reflects our prior analysis, where the majority of solo travelers spent less time in complex terrain (as shown by the low range in the box and whisker plots), while groups of two or more, of which groups of two made up the largest proportion, spent relatively more time in complex terrain.

Finally, the last split, based on posted backcountry avalanche danger rating is also consistent with the prior analysis, with high avalanche danger ratings differentiating from all others this cohort of experts, over 25 and in groups of two or more. This is supported by the data presented in Fig. 4, where we observe 75% of experts spending relatively less time in complex terrain relative to intermediates under high avalanche danger ratings. This difference, while not significant in a group-wise analysis, clearly influenced the split in the GRT.

4.6. Limitations and future work

These results present some valuable insights to the factors that are associated with the increased risk from complex terrain. However, there are several limitations that need to be acknowledged:

4.6.1. Sample and drop-off rate

While substantial efforts were made to attract and enroll participants into the research (Johnson & Hendrikx, 2021), it is likely there were too many steps required to achieve a "complete" data set. The resultant drop off rate after initially signing on to the project was exacerbated by the use of an "off-the-shelf" solution for the tracking and combining it with standard survey software. A custom smartphone application, with an embedded surveys and GPS tracking would result in more efficient participant workflow and would likely have supplied more complete data. Future work should use integrated systems, which are now readily available. In terms of processing efficiencies, future work could develop automated algorithms to remove "extra" sections of GPS track that extend beyond travel in backcountry terrain.

4.6.2. Influence of GPS tracking on decision making

Some participants question the impact of GPS tracking on the sample data collected. While we cannot completely rule out the possibility that this may have influenced some decision making, due to an explicit awareness that they were sharing these data with us, we suspect that the impact was very limited. This assumption is based on the receipt of numerous tracks, where GPS tracking continued well beyond the trailhead. Participants simply forgot they were being tracked. This seems to support the idea that the process of tracking was not fore-front in their mind, and impacting their decision making.

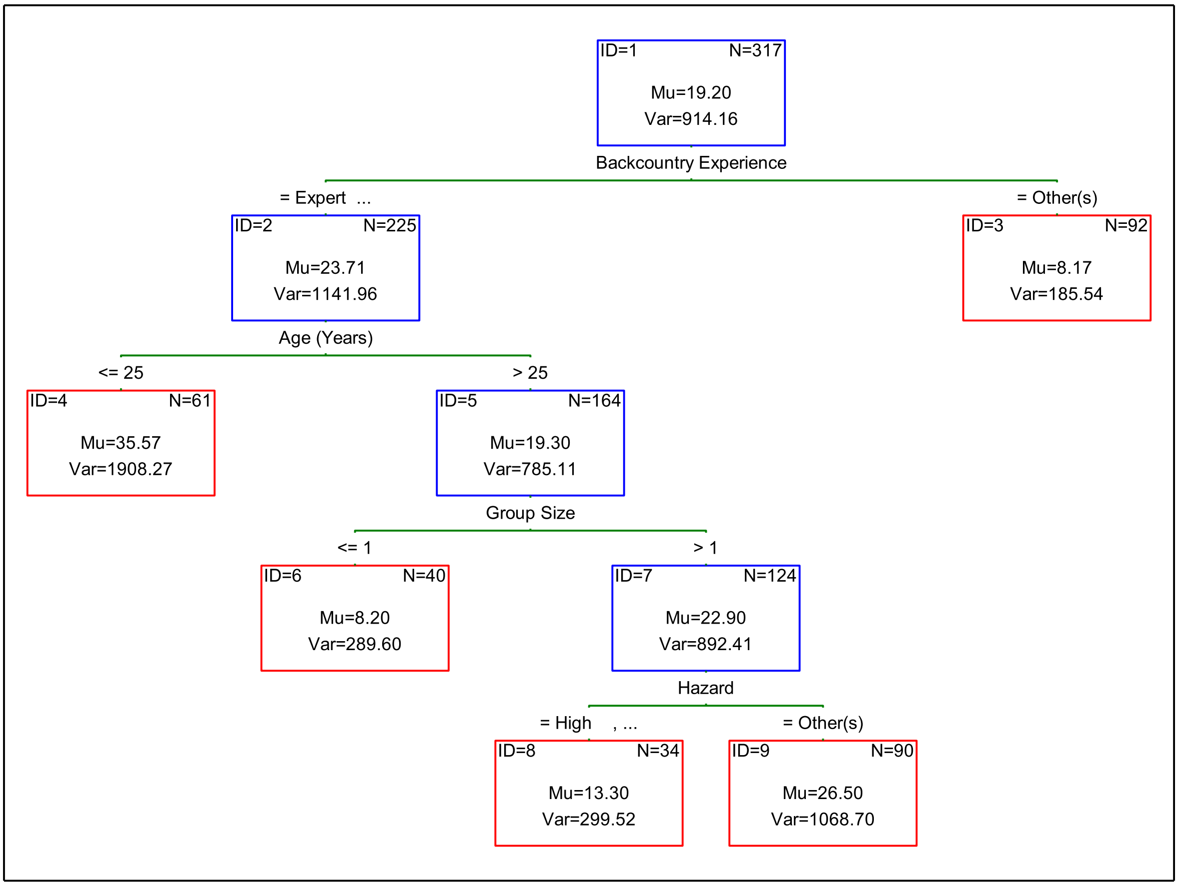

Fig. 7. A generalized regression tree model showing the binary splits, and subsequent splits that best discriminate the data set into the most homogenous nodes for the amount of time in complex terrain (TimeATES3) in minutes.

4.6.3. *Analysis of risk*

We used the percentage of time in complex terrain as defined by ATES, and then categorized this by regional avalanche danger rating. While this provides insight to the overall risk of the track with respect to time, it is clearly not a perfect metric, and distance in ATES terrain could also be considered more carefully. The local within-region differences are not accounted for (i.e. spatial variability of the snowpack), and neither are micro-terrain features (e.g. walking up steep wind scoured ridgeline to then ski safer terrain on the other side). Future work could develop an integrated risk metric that explicitly accounts for both time and distance in ATES terrain and posted regional avalanche danger rating, and also allows for subtle modification as a function of known terrain features. Alternative versions of a quantitative risk measure, using different frameworks have been proposed by Schmudlach and Köhler (2016) and Schmudlach et al. (2018). Furthermore, future work should also leverage ongoing developments with ATES, which will include a new “extreme” class terrain rating that is more exposed than the complex terrain.

4.6.4. *Terrain analysis*

There are also some data limitations as expressed through the smoothing of terrain features smaller than the mean grid size of the DEM used. For the work presented here we used a commonly available 10m DEM. For other applications (e.g. fine scale accident analysis) or more limited geographic areas higher resolution DEMs (e.g. 1m LiDAR) might be more appropriate when available. It could be that significant avalanche features the skier copes with are <10m in size such as small terrain traps, rollovers, etc, and these are lost in smoothing.

4.6.5. *Group decision making*

Responses are from the individual that completed the survey. Replicating these efforts but having all members of the group respond would provide insights into group decision making processes, individual preferences, group differences, and the resulting outcomes. Clearly group dynamics play a role in how and where the group will travel, and these are missed with the use of single respondent surveys.

4.6.6. *Sample*

Finally, our sample of participants are a self-selected sample, which likely means that we have the more engaged, and more aware backcountry travelers represented. This has implications for our scope of reference, suggesting that our results may not be entirely representative of the wider backcountry community, and may display decision making towards the safer/more conservative end of the spectrum (i.e. a “longevity” bias?). This may also be a trait of those users with interest in electronic tracking and surveys.

To address this, a nested discrete choice style experiment (e.g Haegeli et al., 2010; Mannberg et al., 2018; 2020), where choices can be viewed within a more isolated geographical area and only a few degrees of freedom need to be considered could be undertaken. This would also allow for further examination of individual and group decision making practices especially if the experiment involved groups of participants making decisions together. A large sample of participants would allow for segmentation by experience, gender, group size, avalanche danger rating etc. An approach like this would help control for a number of the terrain and snowpack differences that are challenging with real-world GPS tracking. However, such surveys do not force participants to assume the real costs of their decisions.

Despite these limitations, we consider that this approach has provided valuable additional insight into decision making in complex terrain by a cohort of backcountry travelers under a range of group, experience, and avalanche danger rating. The method, with modification, could provide utility for tracking movement in other high risk/low probably settings where small groups make decisions in complex terrain, and where the confluence of terrain, hazard, and human decision making combine to mitigate potential accidents in complex settings (e.g. Wildland firefighters/Military personnel etc.).

4.7. Implications

The implications of these results are that for the first time, we have a complete view of the demographics, behaviors, and terrain usage by a large and geographically diverse cohort of backcountry travelers under a range of group size, skiing and avalanche experience, and across the avalanche danger rating. These data, as a cohesive and combined set, have until now not been available. These data, while still presenting some challenges with respect to the isolation of key driving variables in high stakes decisions, provide insights into real time decision making by tracking users' real-world actions, and the factors associated with these decisions, and the resulting terrain usage as described by use of complex terrain. These results show the importance of geography as a driving variable of decision making, and for a framework like ATES that permits classification of terrain so that user preferences can be quantified with regards to exposure to avalanche terrain. These results build on similar geographic analysis that examine user preferences for skiers (Rupf et al., 2011) and snowmobilers (Kliskey, 2000) but expand to include the demographics and decision-making aspects.

The work by McCammon (2004) suggested that avalanche education and overall proficiency might increase the likelihood of an avalanche fatality. We focused on the self-assessed backcountry skills of the participant, and we showed that in our data set, for both the number of years of skiing and technical difficulty of ski terrain the difference between intermediate and expert groups were statistically significant. Our data shows that expert backcountry travelers will likely expose themselves to more severe terrain, and spend longer in complex terrain, but we make no statement about the resulting likelihood of avalanche fatalities by this group. Indeed, skills training, like that found in avalanche education, is intended to expand the ability of participants to utilize wider terrain choices as they progress in experience and ability.

Using the measure of backcountry experience as a variable, we can clearly see that there is a statistically significant difference for a number of the avalanche competency questions, and some of the decision-making processes. Based on these results we can infer that compared to intermediates, experts ski more technical terrain, have higher BC skiing skills, higher (perceived) transceiver competency, have greater (perceived) terrain management skills, have more avalanche education, have higher (perceived) confidence in their snowpack assessment skills, try to determine the snowpack issues, use a well-defined process, and create plan before communication. One might anticipate that these differences are sufficient to outweigh the more serious terrain risk that experts tend to engage, and therefore reduce their susceptibility to avalanche accidents, however the results from McCammon (2004) suggested that this may not entirely be the case. Furthermore, recent trends in the age of avalanche victims (which is highly correlated with experience) in Switzerland (Winkler and Techel, 2014) and the USA (Peitzsch et al., 2020) suggest that age, and experience may not be sufficient to compensate for this additional risk.

Finally, this work also shows the importance of group factors, specifically group size, group composition, and familiarity with ski partner. These findings are consistent with other factors examined by Mannberg et al. (2018; 2020), and highlight the importance of social and group factors on our resulting decision making in avalanche terrain.

Overall, the findings point to the importance of understanding how the demographics and human factors are associated with terrain use of backcountry riders. We document significant differences in terrain use between those with high levels of experience and skills and those with less. Clearly, while travel in avalanche terrain is potentially hazardous, experience and skills seem to enable riders to exploit more complex terrain and so push their personal limits in the sport.

5. Conclusion

The primary research problem for those who study avalanche and other similar accidents is the difficulty of simultaneously tracking both the terrain usage and decision-making processes of small groups of widely dispersed recreationists in winter conditions. Our methods lend considerable investigative power to that problem and stand in stark contrast to post accident forensic analysis.

In this paper we have presented the results of our crowd sourcing data collection which successfully combined GPS tracking with online surveys on multiple user platforms in an effective method for tracking movement, ascertaining decision points and observe terrain usage by small groups of winter backcountry travelers.

We provide a robust metric for defining backcountry skier experience, and show quantifiable differences in how decisions are made, and how terrain is used under different avalanche danger ratings as quantified using ATES. Specific to experience, we can clearly see that there is a statistically significant difference between self-identified intermediates and experts for a number of backcountry competencies, including scores for BC skiing skills, transceiver competency, terrain management skills, confidence in their snowpack assessment skills, and avalanche education (all higher for experts), In terms of decision making processes, there also seem to be differences for experts, in that they are more likely to try to determine real issues, use a well-defined process, and create a plan before communication.

Specific to their terrain used, experts also had an increased exposure to avalanche terrain, when expressed as a percentage of their track, with higher percentages in all ATES classes. In terms of total time spent in ATES terrain in general, and class 3 ATES terrain, experts also had a higher median time exposed. Furthermore, experts were in this terrain more than intermediates, across all regional avalanche ratings, except high/extreme regional avalanche ratings. We also examine the impact of group size and group composition, and group factors including partner familiarity. We show that experience is important in terms of the severity of avalanche terrain use, with experts spending more time in complex terrain.

Finally, we propose that our methods may be expanded to other high risk/low probability events where geography and decision processes may play an important role in accident avoidance.

CRediT authorship contribution statement

Jordy Hendrikx: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Writing – original draft, Project administration, Funding acquisition. **Jerry Johnson:** Conceptualization, Investigation, Methodology, Survey Design, Formal analysis, Writing – review & editing. **Andrea Mannberg:** Survey Design, Investigation, Methodology, Writing – review & editing, Funding acquisition.

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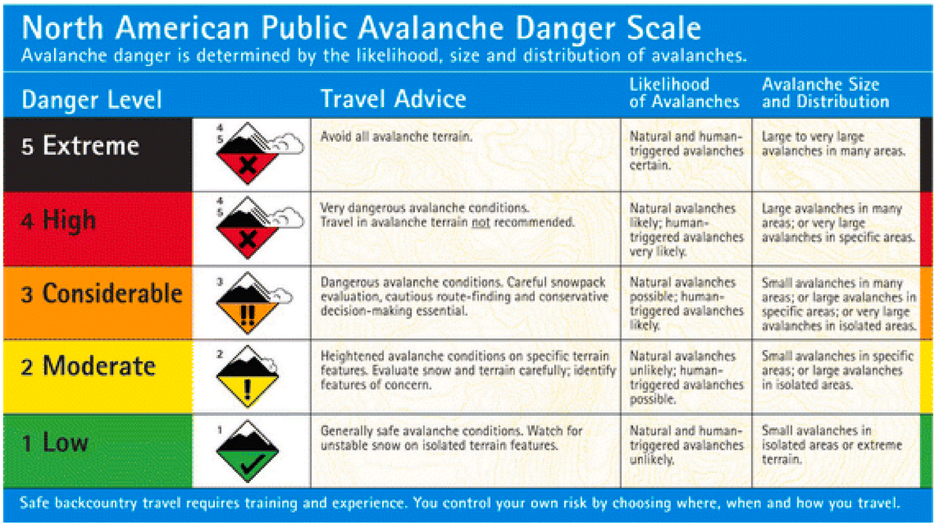
Appendix 1

The North American public avalanche danger scale (Statham et al., 2018).



North American Public Avalanche Danger Scale

Avalanche danger is determined by the likelihood, size and distribution of avalanches.

Danger Level		Travel Advice	Likelihood of Avalanches	Avalanche Size and Distribution
5 Extreme	4 5	Avoid all avalanche terrain.	Natural and human-triggered avalanches certain.	Large to very large avalanches in many areas.
4 High	4 5	Very dangerous avalanche conditions. Travel in avalanche terrain not recommended.	Natural avalanches likely; human-triggered avalanches very likely.	Large avalanches in many areas; or very large avalanches in specific areas.
3 Considerable	3	Dangerous avalanche conditions. Careful snowpack evaluation, cautious route-finding and conservative decision-making essential.	Natural avalanches possible; human-triggered avalanches likely.	Small avalanches in many areas; or large avalanches in specific areas; or very large avalanches in isolated areas.
2 Moderate	2	Heightened avalanche conditions on specific terrain features. Evaluate snow and terrain carefully; identify features of concern.	Natural avalanches unlikely; human-triggered avalanches possible.	Small avalanches in specific areas; or large avalanches in isolated areas.
1 Low	1	Generally safe avalanche conditions. Watch for unstable snow on isolated terrain features.	Natural and human-triggered avalanches unlikely.	Small avalanches in isolated areas or extreme terrain.

Safe backcountry travel requires training and experience. You control your own risk by choosing where, when and how you travel.

Appendix 2

2A

Mann-Whitney *U* Test (with continuity correction) with tests significant at the $p < 0.05$ level results shown in **bold**. Intermediate ($n = 121$) vs Expert ($n = 301$). A copy of our pre-trip survey, and post-trip survey are available in Johnson and Hendrikx (2021), as supplementary materials.

Variable	U	Z	p-value	Z adjusted	p-value	Intermediate (median)	Expert (median)
Snowpack Assessment	1575	−6.10	0.000	−6.73	**0.000**	5 (Moderate Confidence)	3 (High Confidence)
Terrain Management Ability	1363	−6.78	0.000	−7.06	**0.000**	3 (High Confidence)	4 (Highly Proficient)
Transceiver competency	1708	−5.68	0.000	−6.06	**0.000**	4 (Very Proficient)	5 (Extremely Proficient)
BC Skill level	1716	−5.65	0.000	−5.99	**0.000**	3 (Level III)	4 (Level IV
BC Skiing Terrain	1982	−4.80	0.000	−5.05	**0.000**	3 (High Confidence)	4 (Highly Proficient)
Avalanche Education	2263	−3.91	0.000	−4.21	**0.000**	3 (Level 1)	4 (Level 2)

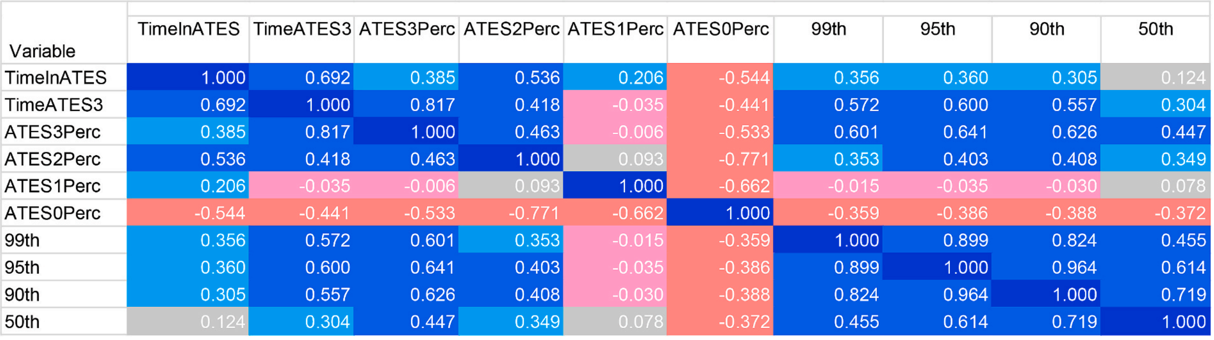
2B

Mann-Whitney *U* Test (with continuity correction) with tests significant at the $p < 0.05$ level results shown in **bold**. Intermediate ($n = 121$) vs Expert ($n = 301$). A copy of our pre-trip survey, and post-trip survey are available in Johnson and Hendrikx (2021), as supplementary materials.

Question	U	Z	p-value	Z adjusted	p-value	Intermediate (median)	Expert (median)
Q1. First Tracks	3182	−0.97	0.330	−0.98	0.327	3 (Occasionally)	4 (Sometimes)
Q2. Goal	3481	0.02	0.983	0.02	0.983	5 (Frequently)	5 (Frequently)
Q3. Other Skied	2970	−1.65	0.099	−1.77	0.077	2 (Rarely)	3 (Occasionally)
Q4. Familiar	3300	−0.60	0.550	−0.65	0.513	2 (Rarely)	2 (Rarely)
Q5. Confidence	2949	1.72	0.086	1.80	0.072	3 (Occasionally)	2 (Rarely)
Q6. Decision On Own	3287	−0.64	0.522	−0.68	0.497	5 (Frequently)	5 (Frequently)
Q7. DifftoImpl	3148	1.08	0.279	1.22	0.224	3 (Occasionally)	3 (Occasionally)
Q8. InclRat	3393	0.30	0.763	0.35	0.729	5 (Frequently)	6 (V. Frequently)
Q9. SupportFriends	3391	−0.31	0.758	−0.33	0.742	5 (Frequently)	5 (Frequently)
Q10. ImplPlan	2852	−2.03	0.043	−2.16	**0.031**	4 (Sometimes)	7 (Always)
Q11. Well defined	2786	−2.24	0.025	−2.35	**0.019**	4 (Sometimes)	6 (V. Frequently)
Q12. SurprisedByCons	3477	−0.03	0.973	−0.04	0.969	2 (Rarely)	2 (Rarely)
Q13. RealIssue	2702	−2.51	0.012	−2.71	**0.007**	4 (Sometimes)	6 (V. Frequently)
Q14. Evaluate	3130	−1.14	0.255	−1.28	0.199	5 (Frequently)	6 (V. Frequently)

2C

Correlation matrix for slope percentiles, percentage of track in ATES terrain and time in ATES terrain.



Variable	TimeInATES	TimeATES3	ATES3Perc	ATES2Perc	ATES1Perc	ATES0Perc	99th	95th	90th	50th
TimeInATES	1.000	0.692	0.385	0.536	0.206	-0.544	0.356	0.360	0.305	0.124
TimeATES3	0.692	1.000	0.817	0.418	-0.035	-0.441	0.572	0.600	0.557	0.304
ATES3Perc	0.385	0.817	1.000	0.463	-0.006	-0.533	0.601	0.641	0.626	0.447
ATES2Perc	0.536	0.418	0.463	1.000	0.093	-0.771	0.353	0.403	0.408	0.349
ATES1Perc	0.206	-0.035	-0.006	0.093	1.000	-0.662	-0.015	-0.035	-0.030	0.078
ATES0Perc	-0.544	-0.441	-0.533	-0.771	-0.662	1.000	-0.359	-0.386	-0.388	-0.372
99th	0.356	0.572	0.601	0.353	-0.015	-0.359	1.000	0.899	0.824	0.455
95th	0.360	0.600	0.641	0.403	-0.035	-0.386	0.899	1.000	0.964	0.614
90th	0.305	0.557	0.626	0.408	-0.030	-0.388	0.824	0.964	1.000	0.719
50th	0.124	0.304	0.447	0.349	0.078	-0.372	0.455	0.614	0.719	1.000

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