CITIZEN SCIENCE:
THEORY AND PRACTICE

Using Citizen Science to Document Terrain Use and Decision-Making of Backcountry Users

RESEARCH PAPER

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ABSTRACT

Avalanches represent the primary risk of death to backcountry skiers and snowmobilers in North American and European alpine countries. The best strategy for evading dangerous snowpack conditions that may result in an avalanche event requires skiers and snowmobilers to avoid or mitigate their use of hazardous terrain. Therefore, understanding terrain use is critical to understanding the causes of avalanche accidents. Secondary, post-event examination of accident data is inadequate for this understanding, and the logistical costs of user intercept surveys are problematic. Learning more about the behaviors and practices skiers and snowmobilers use to avoid avalanche fatalities or near misses is the primary concern of the avalanche education and research community. However, the topographical data required for analysis of skier and snowmobiler behavior with respect to terrain use is beyond the capacity of most backcountry skiers to provide via traditional surveys. This paper presents the use of a novel combination of user surveys and Global Positioning System (GPS) tracking to collect detailed terrain-use data from recreationists who voluntarily engage with researchers via active participation in citizen science research projects. We describe the methodology for these observations and present why they represent an effective approach to understand avalanche accidents.

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INTRODUCTION

Backcountry skiing and snowmobiling are rapidly growing (Birkeland et al. 2017) risk-laden sports that take place in alpine mountain settings. Practitioners of backcountry skiing, the subject of this paper, use specially designed equipment to access ungroomed snowfields outside official ski area boundaries and out of the jurisdiction of ski patrol.[1] Because no snowpack stabilization mitigation efforts exist in this unmarked and unpatrolled terrain, it holds potential for avalanches. Backcountry skiers are expected to understand the risks and make efforts, through informed decision-making and terrain-use practices, to minimize risk and practice self-rescue in the event of an accident (see especially, Tremper 2008).

A typical backcountry ski tour consists of a small group of enthusiasts traveling to a ski tour destination after acquiring the detailed avalanche forecast (if available) from an avalanche forecast center in their region. They would then assess their tour plan and make their way to the ski destination—typically a snowfield or alpine summit from which they would determine a descent route based on snowpack stability. The route both up and down would be contingent on multiple factors including ongoing group discussion of weather, time and distance, risk assessment of terrain and snowpack, and group expertise and level of risk aversion. These skills can be acquired over seasons of experience and/or formal avalanche education classes.

Avalanches represent a risk of injury or death to backcountry skiers and snowmobilers (Boyd et al. 2009; Page 2014; Page 2015).[2] Death is due primarily to suffocation (75–85.7%) or trauma (24–25.4%), and 8.9% of victims die due to combined trauma and asphyxia (Boyd et al. 2009; Silverton et al. 2007). Nonlethal injury may also result from being carried over rocks or into wooded forests by the force of moving snow. These may include relatively minor cuts and bruises, broken limbs, and cold injury (Mueller et al. 2019).

Understanding the components that lead to avalanche incidents is critical; however, this in itself is not sufficient to reduce fatalities. Snowpack failure is the ultimate cause of avalanche incidents, but social behaviors and terrain-use practices are proximate actions that lead to snowpack failure. As such, learning more about behaviors and practices that result in avalanche fatalities or near misses is a primary concern of the avalanche education and research community. These may include but are not limited to how terrain-use decisions are made, social group dynamics, and the assimilation of avalanche education (Johnson et al. 2020; Mannberg et al. 2020c). Such insights can come in a variety of ways that provide proxy information (e.g., hypothetical choice experiments [Haegeli et al. 2012; Mannberg et al. 2018a, 2018b] and secondary data from accident reports [McCammon 2004]). Ideally, researchers would observe skier behavior in avalanche terrain in real time, but logistical reality precludes direct observations in most cases. Alternatively, we engage recreationists as citizen scientists to voluntarily provide detailed travel and personal data (e.g., Global Positioning System [GPS] tracks and survey responses) to researchers. These novel data provide important insights into travel behavior (Fitzgerald et al. 2016; Furman et al. 2010), risky decision-making (Chamarro et al. 2013; Dohmen et al. 2011; Haegeli et al. 2012), and group behaviors (Procter et al. 2014; Zweifel and Haegeli 2014) that other methods cannot. As the information is analyzed and assimilated into avalanche education programs, these citizen scientists help support a virtuous cycle that reduces avalanche accidents among the backcountry ski community by directly contributing data that results in improvements in avalanche training curriculums.[3]

Contrary to popular media coverage of avalanche fatalities, avalanches are neither random nor are they unavoidable (Giacona 2017; Branch 2012). A robust infrastructure exists to help backcountry skiers avoid accidents. Several decades of snow science research, including the study of snowpack characteristics and dynamics, has yielded comprehensive in-depth knowledge of snow dynamics, and a set of snowpack tests are readily available to recreationalists. This science has been effectively communicated via a wide-reaching education program for recreational and professionals users, and is presented in numerous books and media (e.g. *Staying Alive in Avalanche Terrain* [Tremper 2008]; *The Avalanche Handbook* [McClung and Schaerer 2006]; *The Human Factor* [by Black Diamond/Powder] [Page 2014; Page 2015], and *Know Before You Go* [https://kbyg.org/]). A network of avalanche forecast centers in mountainous countries (e.g., United States [US], Canada, Austria, Switzerland, Scotland, Iceland, Norway, Sweden, France, Italy, Spain, and New Zealand) provide high-quality snowpack data, expert observations and interpretations of snowpack conditions, and avalanche forecasts to backcountry recreationists. This multipronged approach to avalanche education and forecasting results in backcountry users having a wealth of pertinent avalanche information, even before venturing into potential avalanche terrain.

The easiest way to avoid avalanches is to avoid all avalanche-prone terrain; however, from a recreation standpoint, this is not viable for most users because the more favorable ski terrain is often also potential avalanche terrain. Therefore, evading dangerous snowpack conditions that may result in an avalanche event requires skiers to avoid or mitigate their use of hazardous avalanche terrain as they travel in the backcountry (typically defined as slopes between 30° and 45°). This is recognized as the single best method to avoid avalanche accidents and is a critical strategy because in 90% of all cases, the victim or a member of the victim's group is the triggering mechanism. Over the past 10 winters, an average of 28 people died in avalanches every year in the US (Greene 2020). An unknown number of "near miss" accidents occur each season. The numbers are higher in the European Alps, where snow avalanches claim an average of 100 lives each year (EAWS 2020).

If we are to better understand the causes of avalanche accidents and resulting fatalities/injuries, we need better knowledge of how snowpack information and terrain-management skills are applied in potential avalanche terrain by potential victims. However, large-scale direct surveys of the backcountry skiing population are difficult, time consuming, and expensive (Procter et al. 2014). The fundamental barrier is that a relatively small number of recreationalists are widely dispersed in remote mountain settings in small groups, so conducting in-person intercept surveys is problematic, limited to a specific cohort, or very limited in space and time (Hendrikx et al. 2016; Fitzgerald et al. 2016). Data collection is doubly challenging when winter weather conditions add a hazard element for researchers. Our methods rely on the citizen science framework to circumvent these barriers. We crowdsource GPS tracking data and combined it with electronic surveys to investigate terrain-management decisions for backcountry skiers, snowboarders, and backcountry snowmobilers. By mobilizing voluntary participants, we overcome spatial and temporal barriers to our data collection.

Because most avalanche victims are the trigger of the event, our research question is focused on how backcountry skiers use terrain to mitigate their avalanche hazard. We then use follow-up surveys to track demographic and decision process data. Specifically, we address two research questions. The first is, "Can we use citizen science to collect track data from backcountry skiers using a crowdsourcing methodology rather than an intercept survey methodology?" Although this question may seem self-evident, the use of GPS tracking of backcountry skiers is problematic in several respects. GPS signal strength in complex mountainous terrain presents significant technological challenges in deep canyons. Smartphones have limited battery life in cold temperatures. In addition, skiers may be protective of terrain and refuse to participate when they feel their favorite recreation spots may be made public. Follow-up surveys ask participants to invest time after their tour to submit the track and provide additional detailed information. All these factors may represent significant barriers to data collection. Sampling, too, may be impacted as those who choose to participate may express a positive orientation toward the use of tracking technology as opposed to those who do not, thereby resulting in sampling bias.

The second question is, "Can we use citizen science–collected track data to better understand how people move in backcountry terrain, and measure if skiers change their terrain use as a function of the posted avalanche warning level and their level of avalanche education, as measured by slope angle?" GPS tracks are the actual decision footprints of backcountry skiers in real-world avalanche conditions, and provide a method to quantify avalanche risk while ski touring. This is in contrast to surveys, where recall bias may be present. Although the terrain-use decision may be due to a complex mix of factors including weather, avalanche hazard, group dynamics, avalanche education, and more, here we investigate the efficacy of using avalanche hazard information and the simple measure of slope angle to simplify the decision analysis. This may be useful for introductory avalanche education purposes. The use of GPS track data also allows for relatively fine-scale (~10m) analysis of the terrain used, well beyond what a survey question or accident analysis could provide, thus providing the opportunity to conduct slope analysis more precisely.

BACKGROUND

Backcountry skiing—skiing practiced outside of designated ski areas and resorts (i.e., in-bounds skiing)—has increased in popularity over the past several decades (Furman et al. 2010). The increase is attributed to better equipment, the high cost of in-bounds skiing, and better access to winter sport recreation areas (Haegeli et al. 2010), but growth numbers are difficult to come by. Birkeland et al. (2017) have postulated, using a variety of indicators, that the total number of users is growing significantly, but the death rate is decreasing or stabilizing over time (e.g., Birkeland 2016; Birkeland et al. 2017; Jekich et al. 2016).

BACKCOUNTRY SKIING IN AVALANCHE TERRAIN

Adventure sports such as backcountry skiing and riding require participants to assume a certain degree of risk in the search for excitement or unique accomplishment, or to advance their skill level. In the case of backcountry skiing, making prudent terrain-based decisions to circumvent unstable snowpack conditions is the most important strategy for safe travel. Traditionally, the method for acquiring terrain-management skills is to enroll in an avalanche education course(s) and then apply this new knowledge, allowing the individual to safely increase their risk seeking or skill building. Although there is a strong culture of education in the sport, education is, of course, optional for practicing backcountry skiing and some may choose to pursue no formal avalanche education opportunities. Others, with a high level of skiing ability honed at developed ski areas, readily embrace backcountry skiing as a way to expand their skiing experience but often do so with little to no understanding of backcountry hazards.

There is a variety of avalanche types across a continuum, from dry to wet and from cohesive to loose, but slab avalanches are the most common type in the case of avalanche fatalities. Slab avalanches are precipitated by three technical conditions: an existing snowpack structure consisting of relatively weaker layers below relatively more cohesive "slab" layers, an existing slope angle sufficient to overcome the friction between layers (typically between 30° and 45°), and a trigger event that causes failure in this weak layer, resulting in the release of the avalanche. Gradations of snowpack instability are designated using the North American Avalanche Danger Scale (Statham et al. 2006), and are indicated via avalanche forecast centers in the US and Canada.[4] Understanding the various types of avalanche hazard is important because different snowpack conditions may require skiers to make different terrain decisions.

AVALANCHE ACCIDENTS

Most research on avalanche accidents focuses on post-incident forensic studies rather than direct observation of skier practices (McCammon, 2004). These depend on accident reports of varying quality and participant recollection, and are thus an imperfect method for understanding accident causes. Reports are subject to several inherent biases that can distort conclusions. Among these are: sampling bias, base rate bias, analysis bias, the group-wise comparison bias and the hindsight bias (Johnson et al. 2020).

The causes of avalanche accidents are examined according to two key paradigms—snowpack failure and human failure. The first approach looks to the reasons for failure of the physical snowpack to determine why an avalanche occurred. The second looks to the characteristics of victims and the decision process that placed them at risk of avalanche. The avalanche education and research community has defined the latter set of circumstances as "human factors."[5]

CITIZEN SCIENCE FOR SNOW SCIENCE

To more fully understand the behaviors associated with potentially risky behavior, we sought detailed information on two sets of variables to construct risk-taking models. The first set includes demographics (age, avalanche education, gender, etc.) and group dynamics (goals of the day, number in group, leadership structure, skills). These are easy data to collect on a well-designed survey if respondents can be reached. The other set of relatively technical data requirements include location, distance traveled, slope angle, time on slope, slope exposure, and snowpack conditions. These are difficult data for the layperson to collect and record, and may not be known by novice skiers but can be extracted from GPS tracking data.

Citizen science (Bonney et al. 2009) is well developed in fields like ecology, environmental sciences, and astronomy, where there is a long history of nonprofessionals making substantive contributions to the respective science (Wiggins and Wilbanks 2019), but it has only recently garnered increased attention in the realm of snow science (e.g., Pfleging et al. 2013; Christian et al. 2014; Hendrikx and Johnson 2014; Zweifel and Winkler 2015; Fedosov et al. 2016; Hendrikx and Johnson 2016a; Hendrikx and Johnson 2016b; Wikstrom Jones et al. 2018).

In an early example of citizen science in snow science, Birkeland (2001), using helicopter access, utilized six two-person sampling teams to collect data from more than 70 sites across a small mountain range in Montana. This research was designed to expand understanding of the snowpack at a larger spatial scale than possible with a single group. Further, it compressed the temporal scale to a single day, an important element for understanding snow dynamics. More recently, Christian et al. (2014) launched an internet, cloud-based platform, to share detailed snowpack information from a new snowpack measurement instrument (the SP1 snow probe) to improve professional information sharing and snowpack assessment, and shared this crowdsourced snow data in real time. Although the instrument had technical deficiencies, this platform, now known as Mountain Hub, became the foundation for a publicly accessible system for citizen scientists to provide snowpack and avalanche information, which was then used by professional avalanche forecasters. Both the Birkeland and Christian projects required a high level of recruitment by lead investigators and intensive training of volunteers to acquire high-quality data.

Hendrikx and Johnson (2014, 2016a) started a crowdsourced, citizen science approach to collect data on terrain use and terrain management by backcountry skiers. Unique to their work was that no specialized training was needed to be a contributing citizen scientist and participate in data collection. This was the first such work in the snow sciences that collected both demographic and skills information from participants as well as real-time terrain use via GPS tracks. Zweifel and Winkler (2015) utilized volunteered geographic information posted on two social media mountaineering networks, *bergportal.ch* and *camptocamp.org*, to track tours, and then associated with snowpack conditions to determine backcountry avalanche risk.

Finally, Wikstrom-Jones et al. (2018) established the Community Snow Observations (CSO) project. This project combined the activities of scientists and recreationists to broaden understanding of snow, to help improve the spatial and temporal coverage of snow-depth observations in complex terrain, and to relate these to hydrological models and remotely sensed data from satellites.

In addition to these citizen science activities, traditional intercept surveys specific to understanding terrain use and backcountry skier demographics have also been employed (e.g., Proctor et al. 2004; Fitzgerald 2018; Sykes et al. 2020). Although these intercept-style surveys yield high-quality data, they are limited by their spatial and temporal coverage; that is, they represent a small sub-sample of users in a specific area. Saly et al. (2020) addressed this deficincy by using a remote time-lapse camera to document the movement of all users within an area, but this approach has a limited geographic range and works only under favorable visibility conditions. Further, it did not follow citizen science methods as participants were not aware they were being observed and were providing data for future analysis.

METHODS

We enlisted volunteer participants to generate two distinct sets of data. The first data set was volunteered geographic data in the form of GPS tracks during ski tours in alpine backcountry. The second data set was demographic and decision data gathered via electronic surveys. These data sets were combined to reveal risk and travel strategies as skiers encountered potential avalanche terrain. We conceptualize the process of backcountry ski travel by using topography as the central initiating variable of terrain-based decision-making (Grímsdóttir and Mcclung 2006), and where we focus on the most critical component of avalanche avoidance—slope angle. In other words, we assume social interactions, personal risk/reward calculations, group discussions, environmental factors, snowpack problems, and terrain-management strategy are encapsulated by the terrain features skiers encounter and utilize during their tour, and avoidance and mitigation is expressed by the terrain slope angle they chose (Hendrikx and Johnson 2014; Hendrikx and Johnson 2016a; Hendrikx and Johnson manuscript in progress).

If we can establish how skiers negotiate terrain and understand the demographics and social factors associated with terrain use, we may gain insight into behaviors that precede triggering an avalanche. The foundation of our methods is that decision-making preferences are a product of interaction with the topography, and that the GPS track represents that interaction. All data was collected and stored in accordance with the Montana State University Institutional Review Board (IRB) approval (#JJ010919-EX) and following US National Science Foundation data security guidelines. Informed consent was required for entry into the first survey (i.e., the Preseason Survey). If potential participants did not accept the consent statement, they were logged off. This is in accordance with IRB practice. Unique to our approach is that we did not instruct our citizen scientists to collect specific data for us, from specific locations or times, but rather were interested in how they used the terrain as they navigated avalanche terrain—i.e., they and their movements in effect were the data, rather than discrete samples/data collected for us by request.

DATA COLLECTION

We collected high-quality GPS and personal/social data using a three-step approach for which citizen science was highly effective.

1. Preseason survey: Respondents filled out an online survey pertaining to their demographics, skiing ability, and avalanche-related skills. This survey was completed once for each participant (Supplemental File 1: Preseason Survey).
2. Volunteered GPS data: Data was submitted via an online smartphone application once for each ski tour recorded.
3. Daily survey: Immediately following submission of GPS data, respondents filled out an online survey inquiring about their group size, experiences, date and location of the tour, and other tour-specific details (Supplemental File 2: Trip Survey).

We used a large-scale, convenient (nonprobability) sample procedure to actively recruit project participants, all of whom engaged in backcountry skiing (Van Selm and Jankowski 2006). A modified snowball sampling takes advantage of several features of the backcountry ski community; that is, their relatively small number, their social cohesion, and demand for high-quality information about snowpack and safety. Our recruitment effort begins with public presentations to the regional snow and avalanche workshops (SAWs) in the western US and Canada. These are typically annual meetings of avalanche professionals and winter backcountry enthusiasts who share snow and avalanche research findings, technologies and techniques for safe travel in avalanche terrain, regional trends in weather and climate, and general interest in learning more about their sport. We printed information sheets and provided links to the preseason survey for potential respondents on a dedicated website.[6] Additionally, we posted a project explanation and signup information through the network of 18 US-based avalanche information and forecasting centers and the centralized Canadian Avalanche Association. We also contacted similar institutions in European alpine countries. In addition, corporate websites and ski-related media were used to attract participants. We actively encouraged participants to engage others (friends, ski partners, club members) in the project (snowball sample). At the end of the northern hemisphere 2016–17 winter season, we enrolled more than 2,000 unique participants from 12 states and Canadian provinces, and 6 alpine countries in Europe.[7]

SURVEYS

We utilize online surveys for maximum access to the backcountry community and as a way to lower their transaction costs of participation, but we recognize several limitations to our methods (discussed below in "Results"). Online surveys are particularly attractive when the population under study is distributed across a large geographic region, and large numbers of potential respondents can be contacted (Van Selm and Jankowski 2006). Further, because the surveys are online and anonymous, we avoid interviewer bias (for example, novice skiers may be intimidated when reporting their travel practices to perceived experts). Finally, for particular populations that are "connected and technologically savvy," the cost, ease, speed of delivery and response, and ease of data cleaning and analysis weigh in favor of an online delivery method for survey research (Sills and Song 2002).

Below, we detail the data collection process in collection order.

Step one: the preseason survey

The preseason survey queried respondents' demographics (age, gender, employment status, participation in outdoor activities) as well as skiing ability and avalanche-related skills (years skiing; experience in backcountry skiing; skill level with terrain management, avalanche transceiver, and snowpack assessment; and avalanche education level). Another section asks participants to respond to questions on decision-making and travel practices while backcountry skiing. This survey is completed once by each volunteer respondent at the beginning of their participation in the project—usually at the beginning of the winter ski season. Completion took about 10 minutes.

Respondents may choose to remain anonymous by using an alias or username that is used throughout their participation so data sets can be linked. A liability waiver statement is provided at this stage and must be accepted to continue participation; we also inform potential participants that the study has undergone university human subjects review. Completion of this survey takes approximately 15 minutes.

Step two: volunteered GPS data

In the next phase of data collection, we ask participants to track their daily tours using a GPS unit or a GPS-enabled smartphone tracking application (*SkiTracks*). At the end of the tour, they submit their tracks to our server by setting up their smartphone to share their tracks with our server. To encourage a broad array of participation, any track format is accepted from any type of apparatus. We encouraged the use of the smartphone application *SkiTracks* because of its ease of use for globally sourced Geographic Information System (GIS) tracks. *SkiTracks* has been designed to use minimal battery power (important for cold conditions) and maintains a high degree of positional accuracy. The application also provides an efficient mechanism to export tracks (as GPX or KMZ formatted files) for analysis within a GIS. Additionally, photos taken while using *SkiTracks* are geo-tagged, so additional geo-referenced metadata and observations can be easily assimilated into our methods (e.g., observed avalanche activity, snow pit profile). Upon completion of their tour, GPS tracks are exported to us directly from *SkiTracks* or another application of their choosing and are submitted to the project email address. Geospatial track information obtained from participants is tagged with the username created when they took the preseason survey. This unique identifier allows us to connect the tracks data with survey data anonymously. ***Figure 1*** depicts tracks for a region near Jackson, Wyoming, USA.

We process each track using a semi-automatic analysis technique using a Python script within ArcGIS 10.4. This process extracts the primary terrain parameters of slope, aspect, and elevation for the entire track from a 10 m digital elevation model (Donovan et al. 2016). Subsequent analysis is then undertaken to extract the remaining terrain-related variables.

After processing, each track contains the following summary statistics: distance; start, end and total time; average, maximum, minimum, and distribution of speed; average, maximum, minimum, and distribution of slope angle; distribution of aspect; average, maximum, minimum, and distribution of elevation; percent of time

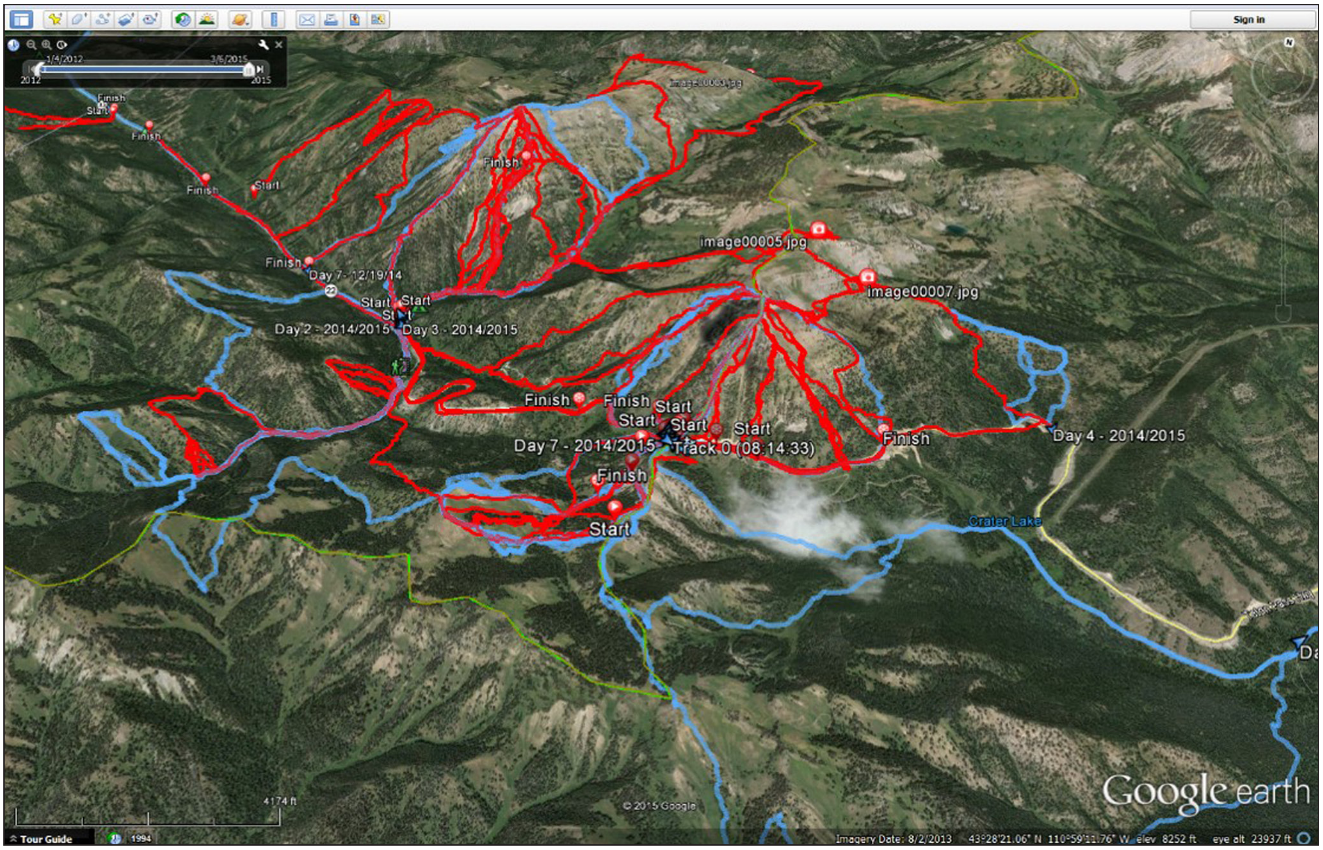

Figure 1 Example GPS tracks sourced from back-country winter users in the Teton Pass area, Wyoming, USA, where tracks in red represent those recorded as self-assessed experts (as defined in our survey), and where tracks in blue represent those recorded as self-assessed intermediates. These tracks were not collected at the trailhead; rather, they are crowd-based GPS track submissions from North American participants.

spent on hazardous slopes over 30°, 35°, and 40°; and posted avalanche warning level.

The continuous variables (e.g., slope angle, percent of time on slopes, and elevation can be examined as probability distribution functions and also with respect to thresholds (e.g., 90th, 95th, and 99th percentiles). Other parameters can simply be calculated as distances or as a binary or ordinal response. Because snowpack and weather conditions often vary from day to day, the choice and number of ski partners may vary, and locations vary, we treat each track of the day as a discreet set of terrain choices even when submitted by the same individual.

Step three: daily survey

The second survey (the daily survey) is initiated by an automatic prompt triggered by the submission of a participant GPS track to the project email after a ski tour. As a way to maximize their participation, participants may submit as many GPS tracks and daily surveys as they like while the survey is open. The daily survey includes the date and location of the tour, the number of people in the touring party, their skill levels, genders, equipment carried, the avalanche hazard for the day, communication and planning questions, snowpack assessment, primary travel mode (i.e., skis, snowmobile, combination), decision processes, and travel practices. All questions are closed-ended for ease of completion on a smart phone. Completion of this survey takes approximately five to ten minutes. By volunteering their GPS tracks, participants supply us with a wide array of technical data in a highly efficient manner and do so with minimal personal effort. Operational definitions of these variables are found in ***Table 1*** below.

RESULTS

SAMPLE SIZE

The first research question asked if we could collect GPS track data from backcountry skiers using a crowdsourcing methodology as opposed to a traditional place-based intercept survey methodology. We suggested that several barriers, including technological and sociological ones, may exist that could preclude successful data collection.

Collecting data using a crowdsourcing citizen science methodology was mostly successful, with both GPS data

VARIABLE	DEFINITION	QUANTITATIVE MEASURE
Avalanche hazard	North American Avalanche Danger Scale	5-point Likert scale
Communication	Did observations and assessment of the snowpack agree/disagree with the local forecast?	Did your observations and assessment of the snowpack agree with the local forecast for the area in which you traveled?
Planning	Snowpack assessment and travel plan discussion	3-point scale: The snowpack was more/less stable than expected so we were/were not able to ski more adventurous terrain/No change to travel plan
Snowpack assessment	Use of compression or beam test during tour	Yes/No
Decision processes	Leader present in group Familiarity with terrain Commitment to goal Commitment to "first tracks" Familiarity with ski partners	Yes/No/Guided 7-point Likert scale—Hi/Lo 7-point Likert scale—Hi/Lo 7-point Likert scale—Hi/Lo 7-point Likert scale—Hi/Lo
Travel practices		
Group experience	Gender, skill level for each member	M/F, Novice/Inter/Expert (respondents are provided with definitions in survey text)

Table 1 Operational definitions of snowpack and human factor variables.

and survey data received. Responses from those who fully participated in our study with a completed preseason survey, a GPS track, and a completed post-trip survey (n = 482) offer some insights to those who practice the sport. Our sample is overwhelmingly male (90%, n = 435) compared with 10% female (n = 47). This is consistent with findings by others (Barlow et al. 2013) in their inventory of risk-taking individuals who practice outdoor adventure sports. The median age of our sample is 31, with a median of 25 years of skiing experience. Most are well educated; 44% have earned bachelor's degrees, and 41% have earned graduate degrees. Most (60%) are single and are employed full time (51%), and 86% have no children living at home. This profile is somewhat counter to the popular conception of high-risk sports being the domain of youthful twenty-somethings and is likely reflective of the relatively high costs of entry to backcountry skiing, as well as our sampling strategy, which is clearly biased toward the more engaged and active sector of the population of active backcountry skiers. This presumed bias is supported by respondents self-identifying primarily as expert skiers (61%), 24% as intermediate, and only 2% as novice. Further, when asked to assess their backcountry skiing skills, nearly 89% self-identify as intermediate or expert.[8]

These results are likely skewed as a function of how we reach potential respondents; most attendees to the regional avalanche workshops are already engaged at a high level in the sport, and novices may not attend education events or visit forecast web sites at the same frequency as more active backcountry skiers. Avalanche education attainment for our sample is as follows: 17% report no formal avalanche education, 4% have attended an evening awareness presentation, 38% completed a level-1 avalanche class, 31% completed a level-2 class, and 10% have taken a level-3 professional class or a guiding course.[9]

Large group size has been cited as a contributing factor to avalanche accidents, and indeed Zwiefel et al. (2012) finds evidence from Italian and Swiss data that solo skiers and those in groups of two are at lower risk than larger groups. Our groups were made up of solo trips (24%), two-person trips (40%), three-person trips (13%), four-person trips (14%), and trips of five or more (8%). Our smaller group sizes are likely the result of our sample representing an overwhelmingly North American population; Europeans tend to ski in larger, often guided groups.

Comparing our volunteer participant sample results with more traditional skier intercept surveys shows similarities with respect to demographics and self-assessment skills (Fitzgerald et al. 2016; Furman et al. 2010; Haegeli et al. 2012; Zweifel et al. 2012), thereby suggesting that active solicitation of citizen scientists as survey participants may yield scienfitically robust samples comparable to intercept survey methods, albiet nonprobability in nature. The lack of probability sampling methods means that generalizations to the larger skiing population cannot be applied.

TRACKS

The second research question queried the efficacy of using slope angle to understand backcountry terrain use given changes in the posted avalanche warning level and different levels of avalanche education. We suggested that GPS tracks represent the decision footprints of backcountry skiers and that slope angle provides a method to quantify avalanche risk while ski touring. Past results indicate that analysis based on voluntarily submitted tracks is useful for understanding terrain-based choices (Hendrikx et al. 2016b; Hendrikx and Johnson 2016c).

We find slope angle to be a simple and highly explanatory variable by which to examine risk in avalanche terrain. We examine the amount of time a skier spends on avalanche-prone slopes (those between 35° and 39.9°), under various avalanche danger ratings, grouped by avalanche education. This example is important because one of the fundamental concepts in avalanche risk management is that the danger level combined with the level of avalanche education may be important determinates of terrain choice (Sykes et al. 2020) To statistically compare the selected terrain metric of percent of time spent on hazardous slopes we used the nonparametric Kruskal-Wallis test (K-W test) to test the differences in the distributions between all of the tracks as grouped according to danger rating or education (see ***Table 2***). As per Hendrikx et al. (2016), working with similar data, we used the K– W test as we had three or more groups, and we selected the $P < 0.05$ significance level (Conover 1999).

This analysis of the data supports the hypothesis that skiers with higher education choose to spend more of their time on steep terrain on lower avalanche danger days, and conversely, on higher-hazard days, higher-educated skiers spend less time on steep terrain owing to increased awareness of the hazard. This relationship is stronger when we consider participants with level-2 and level-3+ avalanche education. When we consider participants with level-1 avalanche education, there is no clear difference in terrain use (as a percentage of time on these slopes) as a function of the hazard. Furthermore, a review of those with no avalanche education (none), also show a difference in their terrain use as a function of the avalanche danger rating. Sample sizes for both the awareness (n = 16) and no education (n = 75) groups were very small and are not statistically significant at the $p < 0.05$ significance level. These findings may have significant implications for avalanche education and accident prevention.

DISCUSSION

CITIZEN SCIENCE SAMPLING EFFICACY

The strategy of using the citizen science framework as an alternative to traditional social science sampling and data generation efforts is effective for several reasons. First, by building our sample based on active outreach to potential volunteer participants via the media and avalanche workshops, we overcome the significant time and logistical costs of traditional sampling and data collection. We were able to collect tracks globally (see ***Figure 2***) and represent skiers from most alpine regions in North America and Northern Europe.

Given the wide geographical footprint of the sport in harsh weather and mountain environments, it is unrealistic both logistically and financially to conduct intercept surveys at more than a trailhead scale. The low density of users adds to the difficulty and cost. Second, we minimize the dropout rate of participants by attracting those with knowledge about the future costs of participation. Once they completed the first phase of the project (i.e., the preseason survey), active participants submitted at least one track and completed the second daily survey. After cleaning the data set for missing data, we acquired a total sample of GPS tracks (n = 770) from 482 participants. However, more than 2,000 people signed up initially for the project. Whereas medical clinical trials studies typically assume a 20% dropout rate (Wu et al. 1980; Shuster 2019), our rate appears to be higher. This might be due to early

AVALANCHE EDUCATION LEVEL	AVALANCHE DANGER RATING				
	N %	LOW	MODERATE	CONSIDERABLE	HIGH
None	20.9	10.1	7.4	2.0	1.4
Awareness	3.2	3.0	–	0.2	–
Level 1	15.6	4.3*	4.4*	2.6*	4.3*
Level 2	20.4	6.7*	6.6*	4.2*	2.9*
Level 3+	15.7	9.6*	4.0	2.1	0.0*

Table 2 Average percent of time spent in terrain with slope angles between 35° and 39.9°, as a function of avalanche education level and avalanche danger rating.
* Significant at the $P < 0.05$ level for group wise comparisons.

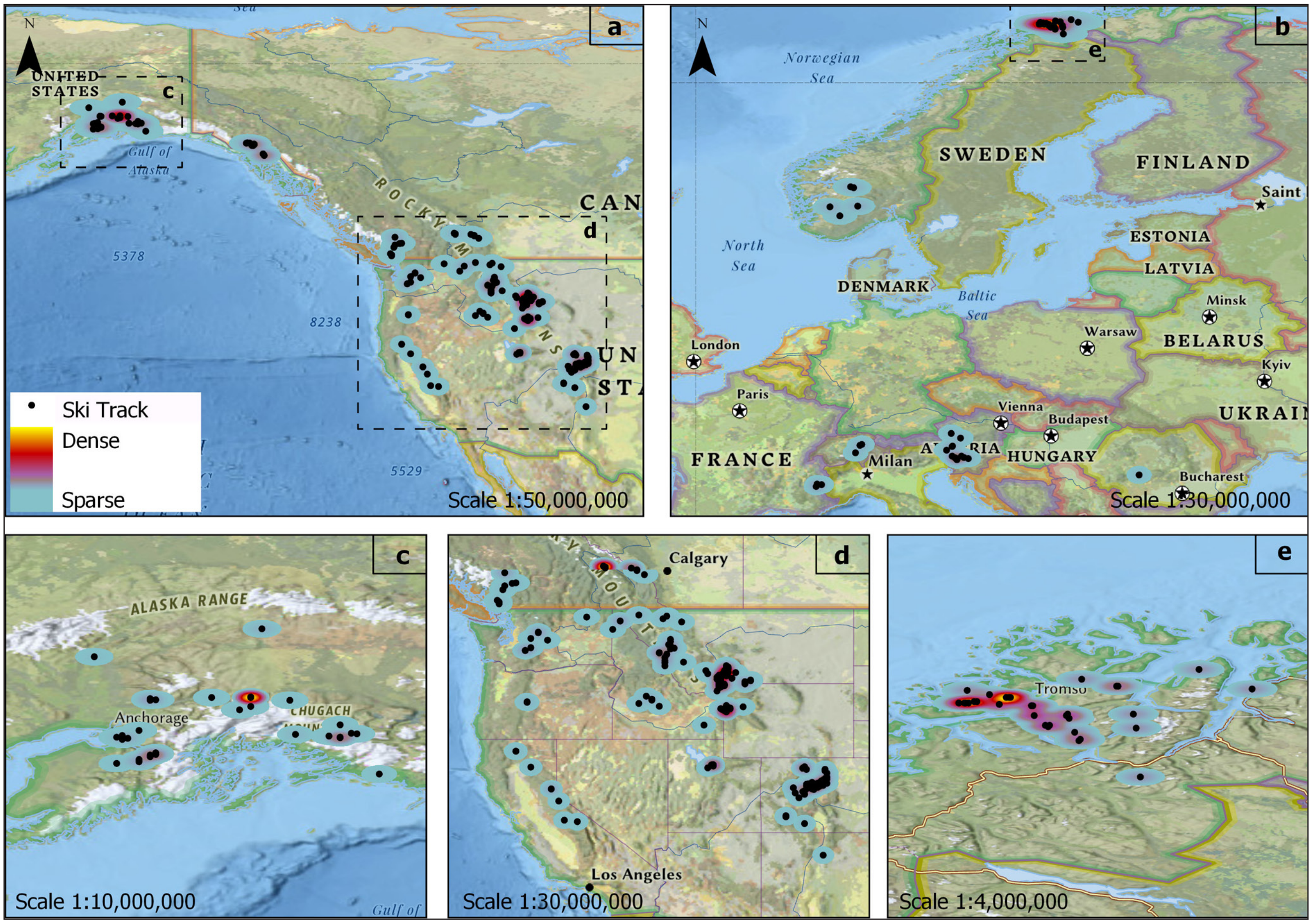

Figure 2 Global maps and detailed inset maps of the collected ski tracks (n = 769), where each point represents the starting point of a given trip, and the heatmap symbology shows the density of points in an area. **(a)** North America, **(b)** Europe, **(c)** inset of south-central Alaska, **(d)** inset of the western United States and southwest Canada, and **(e)** northern Norway. Each point represents the starting point of a given ski tour.

technological barriers in our methods that prevented an easy flow from GPS track submission to the follow-up survey. At the same time, our sample mirrors other studies using intercept surveys, thereby suggesting the citizen science approach can produce high-quality samples for this population. Our methods can be applied to populations of skiers that are accessible to other research and education groups. Findings from specific clientele (i.e., helicopter- or snowmobile-assisted skiers, hut groups, and school outings) could also be investigated using our methods.

TERRAIN USE AND AVALANCHE EDUCATION

Based on our total population of complete GPS tracks (n = 770), with complete survey responses of both the preseason and post-trip surveys, most ski tours do not utilize consistently steep slopes for long periods of time. Rather, tour groups will travel via low angled slopes and occasionally cross or ski down steeper slopes that represent higher potential avalanche risk. Indeed, the median of the 50th percentile slope angles for all our data is only 16°—a slope of virtually no risk for triggering avalanches under normal skiing conditions (unless subject to avalanche hazard from above).

As expected, we found that backcountry skiers with higher levels of avalanche education were more likely to adjust their terrain use toward less steep slopes as avalanche danger levels increased. However, this finding was not true for those with a level-1 education, whereas those who took only an evening awareness class markedly curtailed their travel in avalanche terrain as avalanche danger increased. This suggests a potential weakness in existing avalanche education outcomes, and given the widespread geographical footprint of our participants in multiple alpine settings, the weakness is likely inherent in the education curriculum(s).

Survey data combined with GPS tracking allows for relatively fine-scale analyses of terrain use that are not available using survey-only methods. Using the GPS data, we are able to extract slope-specific slope angles for our analysis that would not be possible with survey data only.

Although we acknowledge that avalanche terrain is defined by more than just slope angle, and includes consideration of aspect, curvature, tree coverage and other snow-related factors, slope angle is the primary factor in avalanche terrain because the slope needs to be sufficiently steep for an avalanche to occur. Although alternative methods using time-lapse cameras (e.g., Saly et al. 2020) can also be employed, when visibility permits, to extract these terrain data, these data are then not associated with any accompanying survey data, and only this combination provides the insights presented here. These terrain insights as expressed via the slope angles used, combined with the survey data, would be impossible to obtain without the cooperation of participants' collection of GPS track data and subsequent survey responses.

AVALANCHE ACCIDENT PREVENTION

Accident investigations of skier behavior and other high-risk sports tend to focus on what went wrong. Post-incident forensic studies are useful but result in less attention on what went right. We suggest that the use of citizen science methods to combine online surveys with GPS tracking and post-trip surveys allows for insight into appropriate decisions about terrain use by backcountry skiers, and such analysis can provide insight into desirable (i.e., less risky) behaviors. Backcountry skiing accidents are decreasing (Birkeland et al. 2017), which suggests most practitioners make decisions that do not result in accidents, and avalanche education coupled with knowledge of avalanche hazard is an efficacious combination for learning good terrain-based decision skills. Deriving the right lessons from our data and ensuring those lessons are clearly articulated in avalanche education can prevent future accidents by illustrating positive learning experiences.

We have demonstrated that by using citizen science techniques and approaches, we can collect a novel and critically missing data set that combines both survey responses and actual terrain use by backcountry users. Our work shows a real-world example in which we use citizen science to collect data on the user rather than only having citizens collect specified data for the scientists. We also show that this data can provide insights that would be very difficult to obtain via intercept surveys. Hendrikx and Johnson (manuscript in progress) will present a full description and more extensive analysis of the data collected in this project.

LIMITATIONS OF OUR DATA AND METHODS

Limitations of the data are clearly evident. GPS tracks and post-trip surveys are not real-time observations of activities, nor do they allow for in-depth analysis of decision processes by groups of individuals. However, the precision of the GPS tracks means we can investigate medium-to-large-scale patterns of backcountry ski travel, and those tracks can serve as the "decision footprint" of ski tour groups. GPS tracks allow for relatively fine-scale terrain analysis, but insight into micro-terrain features that may be important to understanding the trigger point of avalanches is not viable using our current methods and current technology. With time, GPS technology may provide finer terrain detail. Furthermore, our analysis using the terrain metric of slope and percent of time in specific slope angles is a blunt instrument by which to examine precise, detailed terrain decisions, but it does provide general insight into exposure to avalanche terrain, the role of avalanche education, and the use of avalanche danger ratings.

Our findings should not be regarded as the conclusive statement on the causes of backcountry skiing accidents. Clearly, the nature of accidents is more complex (e.g., Johnson et al. 2016; Maguire 2014). Although we provide evidence that avalanche education is positively associated with less risky travel behavior, other contributory factors may be important to reducing avalanche accidents. Decision bias due to specific personality traits, to the role of social media, to the search for status among peers, and to poor communication skills has been associated with accidents (Barbolini et al. 2011; Harvey et al. 2002; Mannberg et al. 2018a, 2018b). In addition, the longer one backcountry skis, the greater the cumulative exposure to an avalanche incident. Finally, there is some evidence that learning theory and student motivations may have an impact on how avalanche education is assimilated by participants, although research is limited (Balent et al. 2018). These are all worthy subjects for future citizen-involved research of both a quanitative and qualitative nature.

CONCLUSION

Citizen science techniques have been applied to collect a unique large-scale data set that describes backcountry users and the terrain they utilize for their sport. These data would have been extremely difficult to obtain across a broad (international) spatial extent using a traditional intercept-style survey approach, which clearly shows the value of citizen science methods.

Backcountry skiing untracked powder snow in mountain settings offers obvious emotional pleasures in a potentially risk-laden environment; risk is an inherent part of that endeavor. Backcountry skiing is also a stimulating mental game where one balances personal risk against group dynamics while considering snowpack analysis and terrain management. Successfully negotiating this complex setting is a multifaceted exercise. Our methods provide a tangible way to document and better understand this complexity in a way that surveys cannot.

The sport of backcountry skiing, like most adventure sports, takes place in a complex setting. The snow medium is opaque and the snowpack unpredictable. As a result, avalanche accidents are an unfortunate consequence of the sport. In this respect, it bears a strong resemblance to other nature-based sports in which practitioners weigh risk and reward (e.g., alpine climbing, whitewater kayaking, and offshore sailing). Our efforts to understand the nature of high-risk decisions of backcountry skiers through their use of potentially hazardous slopes share many of the difficulties of studying other adventure sports. Participants are few and widely dispersed, they interact with a harsh survey environment, there is no baseline population for sampling purposes, and all navigate a complex decision-making matrix aimed at maximizing enjoyment while managing risk. We therefore suggest that our methods may have application for understanding decision-making in other risky sports where what people say they do on traditional surveys and the geographical track (what people actually do) may differ. These data are most easily and effectively collected using the citizen science participation approach.

The goal of human factor research for understanding avalanche accidents (and near misses) is ultimately to reduce accident events. Citizen participation to collect complex and high-quality data yields valid research findings that make their way into avalanche education programs relatively quickly owing to the system of regional SAWs, sport-related media, and the biennial International Snow Science Workshop conference, which attracts both the research and professional education communities. This rapid assimilation offers direct feedback to the skiing community as a result of citizen involvement whereby recreationalists can realize the added value of their participation. Others (Hano et al. 2020) have similarly noted the value of applied research as a result of the citizen scientist approach.

NOTES

1 Backcountry skiing is known as off-piste in Europe and is also referred to as alpine touring or sidecountry skiing. We use the common North American term backcountry skiing throughout this paper.

2 We use the term backcountry skier to describe all backcountry users in general including snowmobiler, skier, snowboarder, or telemark skier. The focus of this paper is on backcountry skiers and snowboarders.

3 Avalanche education in both North America and Europe follows a logical progression from short-term introductory evening sessions to multi-day classes. The American Avalanche Association endorses the following training progressions for recreationists and professionals who make decisions in avalanche terrain: *https://avalanche.org/avalanche-courses/#course-progression*. All other alpine countries follow a similar progression and course content.

4 The North American Avalanche Danger Scale used by avalanche forecasters to communicate the potential for avalanches consists of five levels: Low, Moderate, Considerable, High, Extreme. A similar scale is used in the European alpine countries.

5 The avalanche community definition of human factors is narrower than others. The World Health Organization (WHO) defines human factors as the relationship between human beings and the systems with which they interact. This may include machines, other humans, or personal attributes. Traditional human factors research assumes the "perfectibility" model, which assumes that training will avoid error, whereas the modern view is errors will be avoided if human behaviors, abilities, limitations, and other characteristics are more clearly understood and managed.

6 *www.montana.edu/snowscience/tracks.*

7 Because of the language barriers and the differing ski seasons, we did not solicit participants from Asia, New Zealand, or Andes countries.

8 Respondents were provided a short description for each skier classification in order to self-identify their expertise.

9 Avalanche education follows a tiered progression—evening awareness classes, and then levels 1, 2, and 3. Comparisons across countries follows this progression for recreational and avalanche professionals.

SUPPLEMENTAL FILES

The Supplementary Files for this article can be found as follows:

- **Supplemental File 1.** Preseason Survey. DOI: *https://doi.org/10.5334/cstp.333.s1*
- **Supplemental File 2.** Trip Survey. DOI: *https://doi.org/10.5334/cstp.333.s2*

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The authors have no competing interests to declare.

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