forecast (or bulletin) rates the avalanche danger as either Low, Moderate, Considerable, High or Extreme (Canadian Avalanche Association, 2007).

In western Canada, forecast regions vary from 100 km^2 to almost 30,000 km^2 (Jamieson *et al.*, 2007). The largest regions are approximately 250 times larger than the smallest region and 2,500 times larger than the scale of a ski tour (approximately 10 km^2). In this study, we made local observations in the forecast regions for the North Columbia Mountains, Glacier National Park and the South Columbia Mountains, as shown in Figure 1. For the analysis we used the latest regional danger rating available to recreationists in the morning of the observation day (Jamieson *et al.*, 2007). This was often published 1-2 and occasionally 3 days before the field observations and rating of local avalanche danger.

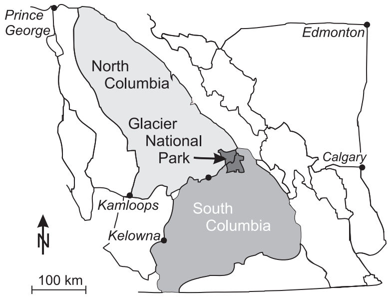

Figure 1. Avalanche bulletin regions in which the observations were made.

2.2 Simple weather, snowpack and avalanche observations

There are many simple weather, snowpack and avalanche observations that are potentially relevant to assessing the local avalanche danger. For this study, we focused on variables (Tables 1 and 2) based on their inclusion in avalanche books for recreationists (e.g. Tremper, 2001, 88-170; McClung and Schaerer, 2006, 197-206), and their ease of observation. Values were assigned to achieve repeatable observations by different observers, or in few cases based on observation guidelines (Greene *et al.*, 2004; Canadian Avalanche Association, 2007). For all but the categorical variable for snow surface condition, we ordered the values or levels based on their expected correlation with avalanche danger. For example, when probing the top 50 cm of the snow surface with a ski pole, gradually increasing resistance is not associated with slab avalanching, a sudden increase in resistance due to a buried crust is sometimes associated with slab avalanching (Jamieson, 2006), and feeling decreasing resistance indicative of hard layers over softer layers is more often associated with slab avalanching.

The rightmost column of Table 1 shows the data type: categorical, ordinal, interval or ratio. Although SkiPen, PrecipRate, HN24, HN48 and TempTr24 are naturally ratio variables, we analyzed them as ordinal variables because their values were estimated and not measured.

A few of the variables warrant further explanation. A whumpf is an audible collapse of the snowpack underfoot. It occurs under similar snowpack and loading conditions as cracks that shoot out from the skis (Figure 2). Both these phenomena indicate that the properties of the slab and underlying weak layer are favourable to propagating fractures in the weak layer (van Herwijnen and Jamieson, 2007a). In contrast, cracking at skis indicates that the snow surface layer is cohesive and stiff but does not indicate the presence of a critically weak layer. Pinwheeling occurs when a small volume of moist or wet snow rolls downslope accumulating a spiral shape or “pinwheel” (Figure 3).

Figure 2. Photograph of a crack that suddenly shoots out from a ski. This indicates the presence of a slab and weak layer both of which are favourable to skier-triggered slab avalanches.

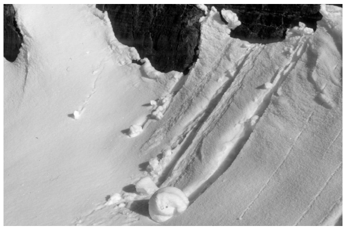

Figure 3. Pinwheels: rolls of moist or wet surface snow on a slope.

A hand shear test is a simple test in which a column, approximately 30 cm by 30 cm, is manually isolated in the top 30+ cm of the snowpack; a slope parallel force is manually applied to create fractures (“shears”) in existing weak layers (Figure 4). The force to cause a fracture is subjectively rated as easy, moderate or hard. For this study, we also noted the character of the fractures, i.e. whether the fractures were planar or not.

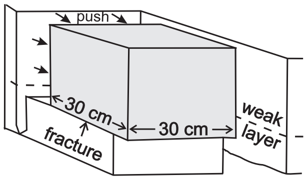

Figure 4. Hand shear test. A column, approximately 30 cm by 30 cm, is isolated about 40 cm deep by hand or with a ski pole. The column is manually pushed downslope and any slope parallel fractures noted.

Table 1. Avalanche and snowpack observations

Variable Name	Description	Values	Data type (sign of correlation)
Avalanche observations			
LoosAvCur	Loose release(s)	None, one or more	Ordinal (+)
SlabAvCur	Slab release(s)	None, one or more	Ordinal (+)
LoosAvRec	Deposit from loose	None, 24 – 48 h old, < 24 h old	Ordinal (+)
SlabAvRec	Deposit or crown from slab	None, 24 – 48 h old, < 24 h old	Ordinal (+)
Passive snowpack observations			
HN24	Snow height last 24 h	cm	Ratio[1] (+)
HN48	Snow height last 48 h	cm	Ratio[1] (+)
ReFreeze	Snow surface refreeze since thaw yesterday	Yes, no	Ordinal (+)
Whumpf	Shooting cracks, whumpfs	None, one or more	Ordinal (+)
Crack	Cracking at skis	None or rarely, common	Ordinal (+)
PinWheel	Pinwheeling	None, one or more	Ordinal (+)
TreeBomb	Snow falling from trees	None, one or more	Ordinal (+)
Drift	Drifted snow deposits	None, one or more	Ordinal (+)
SurfCond	Snow surface condition	Dry fresh, dry settled refrozen crust, wet/moist, wind affected	Categorical
Active snowpack observations			
SkiPen	Avg. ski penetration	cm	Ratio[1] (+)
PoleProbe	Ski pole probing in top 50 cm	Gradually increasing resistance, buried crust, hard over softer layer	Ordinal (+)
HandShearR	Hand shear resistance	Easy, moderate, hard, no fracture	Ordinal (-)
HandShearCh	Hand shear character	Not planar, planar	Ordinal (+)

[1] Ratio variable but the values were estimated and hence the variable was treated as ordinal for analysis.

Table 2. Weather observations

Variable name	Description	Values	Data type (sign of correlation)
PrecipRate	Snowfall rate (cm/h)	According to CAA (2007)	Ratio[1] (+)
WindSpeed	Typical ambient wind speed	Calm, light, moderate, strong According to CAA (2007)	Ordinal (+)
SnowBlow	Blowing snow	None, at ridges, below ridges,	Ordinal (+)
Scour	Wind scouring/ sastrugi	None, one or more affected area/patch	Ordinal (+)
Sky	Cloud cover	Clear, few, scattered, broken, overcast/obscured	Ordinal (+)
TempTr24	24 h change in max air temperature	°C	Ratio[1] (+)
TempTrTdy	Daytime temp increase	< normal, normal, > normal[2]	Ordinal (+)
ReachZero	Air temp to 0°C	No, yes	Ordinal (+)

[1] Ratio variable but the values were estimated and hence the variable was treated as ordinal for analysis.
[2] < normal or > normal implies unusual or anomalous.

2.3 Rating the local danger

On each observation day in the winter of 2006-07, field teams of two or three skilled observers traveled on touring skis to a sheltered site below or at treeline, conducting simple weather, snowpack and avalanche observations as they travelled. At the sheltered site, they performed snow profiles and stability tests as described in Jamieson *et al.* (2006). In addition, they had access to weather, snowpack and avalanche observations from the hosting operation and from neighboring avalanche safety programs. Further, the observers were working throughout the winter in the area, accumulating their knowledge of the avalanche danger.

Using all available information, a danger rating for the local area and the current day, called the “local nowcast” was selected by consensus. The local ratings of avalanche danger used the same five-level scale and definitions as the regional danger ratings (Canadian Avalanche Association, 2007). These local danger ratings were recorded for treeline and below treeline, provided both could be done with confidence. On 46 days, ratings were recorded for both treeline and below treeline, yielding two cases per observation day. On 17 days, the local danger was only rated at treeline or below treeline.

In most days of backcountry winter recreation, groups ascend through terrain less prone or exposed to avalanches and then make a decision about whether to advance into more exposed terrain, or to stay in less exposed terrain. To assess whether the early observations in less exposed terrain were as helpful as the subsequent observations, relevant observations were recorded at the decision point, which often occurred around 11 am, and again at the end of the day. For the preliminary analysis presented in this paper, we combined the observations from before and after the decision point. If the early and later observations differed, we used the one consistent with higher avalanche danger.

3. ANALYSIS AND RESULTS

3.1 Distributions of regional and local avalanche danger ratings

The distributions of the regional and local avalanche danger ratings for the 109 observations in this study are shown in Figure 5.

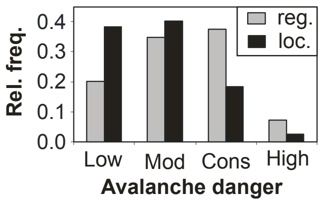

Figure 5. Relative frequencies of regional and local avalanche danger rating.

While the local danger is rated low or moderate more often than the regional rating, the regional rating is rated high or considerable more often. We suspect the generally higher ratings in the regional forecast are caused by the uncertain weather in the days following the publication of the regional forecast, the weighting the regional danger level for specific high use areas within the large forecast regions, and/or “erring on the side of caution” (Jamieson *et al.*, 2007).

3.2 Univariate analysis

Avalanche danger and most of the potential predictors were analyzed as ordinal variables, with the exception of the categorical variable, SurfCond, for the snow surface condition. To assess associations between the ordinal predictor variables and the regional and local danger ratings we used the Spearman rank correlation coefficient r_s (e.g. Walpole *et al.*, 2007, p. 690-691). The results of this analysis are summarized in Table 3.

The rank correlation between the regional danger and local danger (r_s = 0.56) is the strongest correlation of any predictor with the local danger rating, except HN24, which has the same rank correlation as regional danger.

Not including the regional danger rating, fifteen of the variables are significantly correlated with the local avalanche danger and 11 variables with the regional danger (p < 0.05). The fact that the majority of the observed rank correlations are not strong confirms that none of the individual observations is a good predictor of the local avalanche danger by itself. The variables with higher correlations with local danger than with regional danger may be particularly useful for helping recreationists localize the avalanche danger. In the following paragraphs we briefly summarize the results for the most important variables.

The heights of snowfall from the last 24 and 48 hours, HN24 and HN48, exhibit the highest rank correlations with local avalanche danger: r_s = 0.56 and 0.53, respectively. These correlations are expected because of the effect of recent snowfall on avalanching (e.g. Schweizer *et al.*, 2003).

Table 3. Spearman rank correlations of potential predictors with avalanche danger

Variable	No. of data	Correlation with local danger		Correlation with regional danger	
		r_s	p	r_s	p
RegAvDang	109	*0.56*	*10^{-10}*	-	-
LoosAvCur	109	0.03	0.76	*0.21*	*0.03*
SlabAvCur	109	0.09	0.38	0.09	0.35
LoosAvRec	109	*0.28*	*0.004*	*0.34*	*10^{-4}*
SlabAvRec	109	*0.31*	*0.001*	*0.27*	*0.004*
Whumpf	109	*0.45*	*10^{-6}*	*0.27*	*0.004*
Crack	109	*0.28*	*0.003*	-0.02	0.86
PinWheel	109	0.10	0.32	-0.03	0.87
TreeBomb	109	-0.09	0.36	-0.07	0.46
Drift	105	*0.21*	*0.03*	*0.24*	*0.02*
SkiPen	107	*0.32*	*0.001*	*0.46*	*10^{-6}*
PoleProbe	109	*0.22*	*0.02*	0.11	0.25
HandShearR	107	*0.24*	*0.01*	-0.09	0.38
HandShearCh	55	*0.33*	*0.02*	-0.05	0.75
PrecipRate	107	*0.26*	*0.007*	*0.33*	*0.001*
WindSpeed	109	-0.01	0.90	-0.04	0.66
SnowBlow	107	0.12	0.21	0.06	0.43
Scour	109	-0.01	0.90	-0.06	0.55
HN24	104	*0.56*	*10^{-9}*	*0.48*	*10^{-7}*
HN48	93	*0.53*	*10^{-8}*	*0.53*	*10^{-8}*
Sky	104	*0.33*	*0.001*	*0.40*	*10^{-5}*
TempTr24	97	0.08	0.43	0.09	0.39
TempTrTdy	100	*-0.15*	*0.13*	*-0.20*	*0.04*
ReachZero	98	*0.19*	*0.01*	0.001	0.99
ReFreeze	53	*0.28*	*0.04*	0.09	0.53

Correlations for which p < 0.05 are marked in italics.

For the snowpack variables, the highest correlation coefficient is r_s = 0.45 for Whumpf (Figure 6), which is consistently reported to be indicative of instability (e.g. Tremper, 2001, p. 143). There are approximately ten times as many cases without whumpfs as with whumpfs; however, unbalanced data are common in avalanche forecasting and we do not attempt to balance the data in this initial analysis.

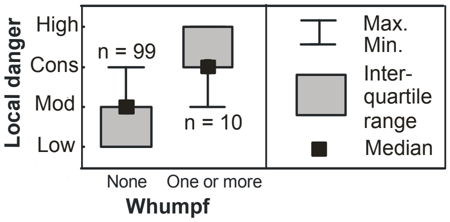

Figure 6. Box and whisker plot of local avalanche danger for cases in which whumpfs were observed and not observed.

The character of hand shears (HandShearCh: planar or non-planar) exhibited a correlation of r_s = 0.33 with local avalanche danger. However, this observation was only made for 55 local danger ratings. The higher correlation for the character over the applied manual load/force (HandShF) is in agreement with the studies of Schweizer *et al.* (2007) and van Herwijnen and Jamieson (2007b) who also found the character or appearance of the fracture to be a better indicator of instability than the loading stage for rutschblock and compression test, respectively.

Observations of recent slab avalanches yielded a rank correlation r_s = 0.31. Not surprisingly, there is a trend towards higher local danger when more recent slab avalanching has been observed (Figure 7).

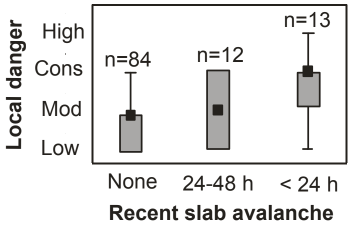

Figure 7. Box and whisker plot of local avalanche danger for the three categories for recent slab avalanches.

The ski pole probe exhibited a significant but weaker correlation (Figure 8) with local danger (r_s = 0.21).

Although the variable Sky is ordinal since it represents increasing cloud cover, the amount of cloud cover does not have an obvious monotonic relationship with avalanche danger. Overcast or obscured sky is common during precipitation which is associated with avalanching, whereas clear sky is also sometimes associated with warming of the snow surface by short wave radiation and potential avalanching. The box plot in Figure 9 shows a weak increase in avalanche danger for increased cloud cover. Had more observations been made in late winter and early spring when the short wave radiation during the longer days can potentially warm the snow surface more, it is possible that higher danger would have been associated with clear sky or few clouds.

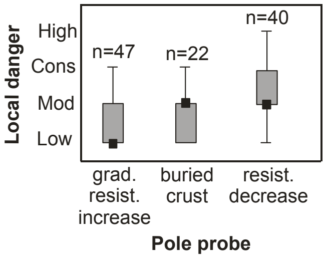

Figure 8. Box and whisker plot of local avalanche danger for the three outcomes from probing the near surface layers with a ski pole.

The analysis of the variable for surface condition, SurfCond, shows that the local avalanche danger tended to increase for the conditions of settled/crusty, wind stiffened, dry fresh and sticky (Figure 10).

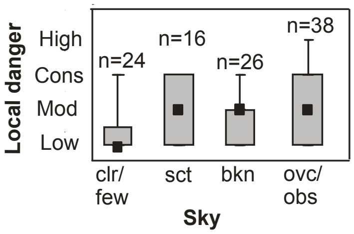

Figure 9. Box and whisker plot for local avalanche danger for four classes of Sky (cloud cover).

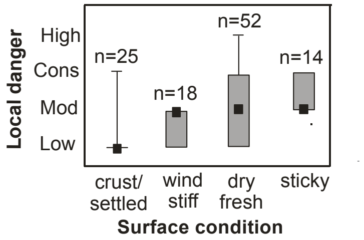

Figure 10. Box and whisker plot of local avalanche danger for four classes of snow surface condition.

3.3 A multi-predictor model for local avalanche danger

The primary goal of the present study is to illustrate how some easy field observations can be combined with the regional danger rating to estimate the local danger. For this analysis, we considered the methods of threshold sums and classification trees.

An example of a threshold sum model used in avalanche safety is the Obvious Clue Method (McCammon, 2001; McCammon and Haegeli, 2007). The Obvious Clue Method provides the user with a checklist of seven questions, each about an observation (Obvious Clue) that has been found indicative of situations that have led to avalanche accidents in the past. The more questions about a backcountry situation that are answered yes, the more clues the situation has in common with past avalanche accidents recorded in a specific database. This is the basis for the field decision side of the Avaluator Accident Prevention Card (Haegeli and McCammon, 2006). While the Avaluator is now widely taught in Canada, a considerable limitation of this approach is that it is purely an awareness tool and does not have any predictive capabilities for avalanche accidents.

To illustrate an alternative method we used a classification tree, which recursively splits the data into two groups using various partitioning rules. Fortunately, the resulting trees tend to reflect structure in the data and are not strongly affected by the partitioning rules (Breiman *et al.*, 1984, p. 94). Classification trees allow for complex relationships between predictor variables, are sensitive to non-monotonic relationships between the predictors and the response variable and allow categorical or ordinal response variables with more than two levels, such as avalanche danger.

For this preliminary analysis we chose potential predictor variables according to the following criteria:

1. relatively highly correlated with the local avalanche danger
2. not strongly correlated with other predictors, including the regional avalanche danger
3. available for almost all cases to maximize the dataset used to build the tree.

From the eight variables in Table 3 with a highly significant correlation ($p < 0.005$), LoosAvRec, SkiPen and Sky were excluded because their correlations with regional danger were stronger than with local danger. We constructed a classification tree for local avalanche danger using the regional danger level and the five remaining variables SlabAvRec, Whumpf, Crack, HN24 and HN48 (Figure 11). The classification tree algorithm is similar to a step-wise regression in that it will reject predictors that do not satisfy criteria 1 and 2. In the case presented, the algorithm also rejected the variables HN24 and HN48, which is not surprising because they are correlated almost as strongly with regional danger as with local danger.

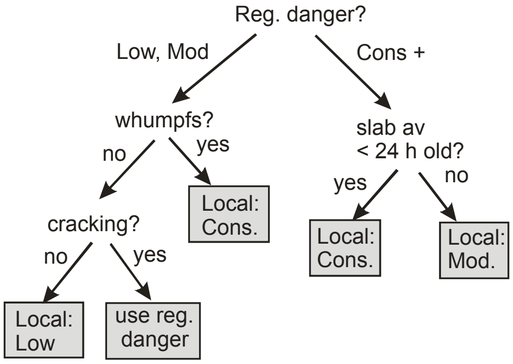

Figure 11. Classification tree for local danger using regional danger and selected local observations.

The rank correlation for the local danger output by the classification tree with all 109 cases for observed local danger is $r_s = 0.66$ ($p = 10^{-14}$). This is higher than the correlation of the observed local danger with the regional danger alone ($r_s = 0.56$, $p = 10^{-10}$). However, this includes eight cases in which the regional danger was High. Since we doubt the relevance of including a few cases with High regional danger (when recreation is not common), we calculated $r_s = 0.65$ ($p = 10^{-13}$) for the 101 remaining cases.

The first branch in the tree is based on the regional danger, which has the highest rank correlation ($r_s = 0.56$) with local danger. The second level branches are based on recent slab avalanches and whumpfs, both of which exhibit higher correlations ($r_s = 0.31$ and 0.45, respectively) with local danger than cracking at ski tips ($r_s = 0.28$). Also, whumpfs or shooting cracks indicate that both the slab and weak layer are favourable to avalanche release, whereas cracking at ski tips at the third level only indicates the near surface layer is cohesive or “slabby” but does not indicate a weak layer favourable to avalanche release.

Similar to the classification tree derived above, the Obvious Clue Method of the Avaluator decision support tool uses recent avalanching and signs of instability such as whumpfs as Obvious Clues (McCammon and Haegeli, 2007; Haegeli and McCammon, 2006). While the clues for the Obvious Clues Method were derived from avalanche incident records, the correlation of these variables with avalanche danger in this study suggests that the association of these variables with the local avalanche danger rating can be used as a more general guideline for identifying increased levels of avalanche danger. In addition, the importance of these variables does not seem to depend on the analytical method.

The classification tree can now be used to “predict” local danger based on the regional avalanche danger rating and the local observations. The tree presented in Figure 11 allows the local danger rating to be assessed either lower or higher than the regional danger, or the same as the regional danger. For example, if the local danger is Low or Moderate and whumpfs are observed, the tree outputs Considerable local danger. If the regional danger is Considerable and no slab avalanches less than 24 hours old are observed, then the tree outputs Moderate local danger.

To assess the quality of the local danger rating “predictions” by the classification tree, we calculate the True Skill Score or Hanssen-Kuipers discriminant, HK, a measure of accuracy calculated relative to random predictions (Wilks, 1995, p. 250). HK is calculated from a contingency table (Table 4) and is given by

$$HK = \frac{\frac{1}{N}\sum_{i=1}^{3} n(P_i, O_i) - \frac{1}{N^2}\sum_{i=1}^{3} N(P_i)N(O_i)}{1 - \frac{1}{N^2}\sum_{i=1}^{3}\left[N(P_i)\right]^2} \qquad [1]$$

where $N(P_i)$ is the number of cases with "predicted" level i (row total in Table 4) and $N(O_i)$ is the number of cases with observed level i (column total in Table 4). HK ranges from $-\infty$ to 1 and is a measure of the improvement over a random forecast, in which a perfect forecast would score 1 and a random forecast would score 0.

Because of the very limited data for High avalanche danger, and the importance of evaluating the tree for the three lower levels of avalanche danger which are most relevant for recreation, the analysis is limited to the 99 cases for which neither the regional nor local avalanche danger ratings were High.

Using the output from the classification tree for the 99 cases with Low, Moderate or Considerable danger, the HK value for the "prediction" of the local danger rating is 0.34. Using the regional danger level as the only predictor of local danger for these cases results in a HK value of 0.12.

Table 4. Contingency table for predicted and observed local danger levels

"Predict-ed" local danger level	Observed local danger level			Row totals
	1 (Low)	2 (Mod.)	3 (Cons.)	
1 (Low)	$n(P_1,O_1)$	$n(P_1,O_2)$	$n(P_1, O_3)$	$N(P_1)$
2 (Mod.)	$n(P_2,O_1)$	$n(P_2,O_2)$	$n(P_2, O_3)$	$N(P_2)$
3 (Cons.)	$n(P_3,O_1)$	$n(P_3,O_2)$	$n(P_3, O_3)$	$N(P_3)$
Totals	$N(O_1)$	$N(O_2)$	$N(O_3)$	N

4. POTENTIAL ISSUES AND LIMITATIONS

There is the potential that certain observations such as SlabAvRec or Whumpf might have a strong influence on the assessment of the local danger rating and therefore should not be used as independent predictors of the local avalanche danger. Although observations such as recent avalanches and whumpfs are important, the influence of an individual observation or variable on the local danger rating is likely weak because

- the observers were working continuously in the area and were rarely surprised by any one observation
- local danger ratings were based on a variety of correlated variables
- in a similar study of snowpack stability tests, Jamieson *et al.* (2006) rated the local danger before and after doing the stability tests, and found that they only changed their local danger rating due to the stability test results in 5 to 8% of the cases.

While the results of this preliminary study are encouraging, 109 sets of observations collected during one winter season and in only one snow climate are insufficient for developing or validating a support tool for backcountry recreation. This is especially true for classification trees, which may not be stable for small datasets. However, the results presented in this study may provide a template for the development of future extensions of the existing decision support tools. (See McCammon and Haegeli (2007) for a summary of existing of decision support tools for avalanche safety).

5. CONCLUSIONS

On 63 days in the winter of 2006-07, a set of 25 easy weather, snowpack and avalanche observations (potential predictor variables) were linked with local ratings of the avalanche danger at and below treeline in the Columbia Mountains, yielding over 100 records or cases. Of the 23 ordinal or ratio predictor variables, 15 exhibited significant rank correlations ($p < 0.05$) with the local avalanche danger. A categorical predictor, snow surface condition, also showed predictive potential. A classification tree was constructed with the regional danger rating and three highly correlated local observations. The local danger rating agreed better with output from the classification tree (r_s = 0.65, HK = 0.34) than it did with the regional danger rating (r_s = 0.56, HK = 0.12) suggesting that regional danger rating can be combined with the local observations to estimate the local avalanche danger. However, there were insufficient data to independently validate the model. Future studies are planned to expand the dataset and hopefully develop a support tool for localizing the avalanche danger for winter mountain recreation in Canada.

The snowpack observations in this study focus on the surface and near surface layers. However, deeper layers can also play an important role in avalanche formation. Jamieson *et al.* (2006) provides a more detailed analysis of the usefulness and predictive merit of snowpack tests of deeper layers. These tests require digging a pit, are slower and therefore less attractive than the easy observations considered in this paper. However, a future support tool may need to include both types of observations to be effective under a wide variety of snowpack conditions.

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