CAN FIELD OBSERVATIONS BE COMBINED SYSTEMATICALLY WITH THE REGIONAL DANGER RATING TO ESTIMATE THE LOCAL AVALANCHE DANGER?

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ABSTRACT: Snow avalanche danger can vary considerably within the large forecast regions in western Canada. Experienced recreationists routinely use the regional bulletin along with local observations to estimate the local avalanche danger. However, some less experienced recreationists are unsure how to interpret the various field observations. To assess a systematic approach, we conducted a field study during the winters of 2006-07 and 2007-08 in the Columbia Mountains of western Canada. Experienced observers rated the local avalanche danger and made 24 observations of weather, avalanche activity and simple manual snowpack tests on approximately 130 location-days. Since the local danger was often rated separately for the elevation bands alpine, treeline, and below treeline, the observations could be applied to 272 individual local danger ratings. Fourteen of the potential predictors yielded significant rank correlations with the local avalanche danger. Reflecting their larger scale, many of the weather variables correlated better with the regional danger rating than with the local rating. In contrast, some snowpack observations including the hand shear and ski pole test correlated better at the local scale than the regional scale. Classification trees using the regional rating plus three or four of the local observations exhibited a better agreement with the local danger rating than did the regional rating by itself.

KEYWORDS: avalanche forecasting, snowpack tests, field observations, classification trees, avalanche danger, scale issues

1. INTRODUCTION

During a typical day of backcountry snowmobiling, snowboarding or ski touring, recreationists are exposed to avalanche paths within an area of roughly 10 km^2. To assess the local avalanche danger during a backcountry trip, recreationists generally have three potential sources of information:

1. the regional avalanche bulletin (where available)
2. various local weather, snowpack and avalanche observations that do not require digging a pit, and/or
3. snowpack observations, notably stability tests, that do require digging one or more pits.

Regional avalanche bulletins generally provide an expert assessment of the avalanche danger in a given forecast region and it seems reasonable for amateur recreationists to use these assessments as initial estimates of the local avalanche danger in the area of the day's recreation. However, many forecast regions in Canada are quite large, and local avalanche danger can vary considerably within these regions (Jamieson and others, 2007). Since some bulletins are only published less than seven times a week, there is also the potential for the regional and the local avalanche danger to differ because the bulletin was published one or more days before the travel day. In addition, many recreationists in Canada travel in areas that are not covered by regional avalanche bulletins.

This study was conducted in the Columbia Mountains, which have a transitional snowpack with a maritime influence in which the midwinter snowpack at treeline is often about 3 m thick. Every winter, surface hoar (frost) buried by subsequent snowfall results in several persistent snowpack weaknesses in the Columbia Mountains (Haegeli and McClung, 2007).

Because of the large spatial and temporal variations in avalanche danger, it is useful to provide amateur recreationists with guidance about how local observations taken during a backcountry trip can be used to locally verify and sometimes adjust the avalanche danger assessment of a regional avalanche bulletin. While

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the study of Jamieson and others (2006) focused on the value of stability tests that require digging, this study examines the value of various simple weather, snowpack and avalanche observations, which do not require digging, for localizing the regional avalanche danger assessment.

Jamieson and others (2008) presented an analysis of observations from treeline and below treeline areas in the Columbia Mountains during the winter of 2006-07. For the winter of 2007-08, the study was expanded to the Coast Range, the Rocky Mountains and into alpine areas above treeline in all three ranges. In this paper, we analyze the data from the Columbia Mountains during winters of 2006-07 and 2007-08. The effect of time of observation (am or pm), vegetation zone (alpine, treeline or below treeline) and the mountain range (Coast, Columbia or Rocky Mountains) will be analyzed for a subsequent publication.

2. DATASET

2.1 Regional danger ratings

Regional avalanche bulletins in western Canada include danger ratings and several short paragraphs of text. The text typically explains how the weather and snow conditions are contributing to the avalanche danger and discusses the avalanche danger in terms of the terrain. The forecast (or bulletin) rates the regional avalanche danger (RF) as either Low (1), Moderate (2), Considerable (3), High (4) or Extreme (5) (Canadian Avalanche Association, 2007).

In western Canada, forecast regions vary from 100 km^2 to about 25,000 km^2 (Jamieson and others, 2007). The largest regions are approximately 2,500 times larger than the scale of a ski tour, which is approximately 10 km^2. In the winter of 2006-07, 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. Glacier National Park produces a daily bulletin in the mornings. In the North and South Columbia Mountains, the bulletin was often published 1 to 2 and occasionally 3 days before the field observations and rating of local avalanche danger. For more on the effect of lead time and forecast area on the regional danger ratings, see Jamieson and others (2007).

2.2 Simple field 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 2 and 3) 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 and others, 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 rarely associated with slab avalanching, a sudden increase in resistance due to a buried crust is sometimes associated with

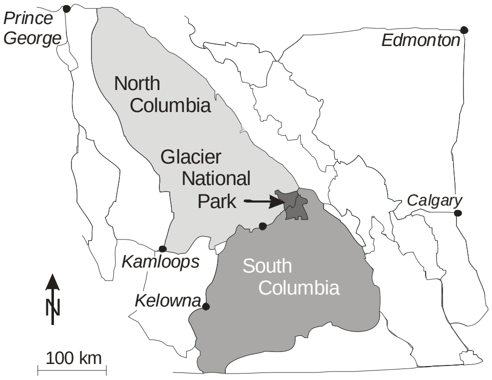

Figure 1: Avalanche bulletin regions in which the observations were made.

Table 1: Summary of data for local nowcasts and regional forecasts

Number of cases (Alp/TL/ BTL)	Sites for local nowcasts	Forecast region (Fig. 1)
0/2/2	North Purcell Mountains	South Columbia Mountains
3/54/73	Cariboos near Blue River, BC	North Columbia Mountains
21/56/61	Highway corridor in Glacier National Park	Highway corridor in Glacier National Park

slab avalanching, and feeling decreasing resistance indicative of hard layers over softer layers is more often associated with slab avalanching.

The rightmost column of Tables 2 and 3 shows the data type: categorical, ordinal, interval or ratio. Although SkiPen, PrecipRate, HN24, HN48 and TempTr24 have the ratio property, we analyzed them as ordinal variables because their values were estimated and not measured.

A few of the variables deserve some explanation. A whumpf is an audible collapse of the snowpack typically induced by movement of a person or oversnow machine. 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, 2007). 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.

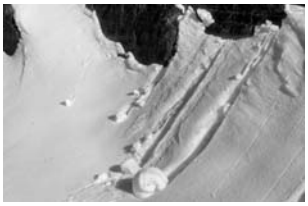

Figure 3: Pinwheels: rolls of moist or wet surface snow on a slope.

A hand shear test is a simple test in which a column, with a cross section about 30 cm by 30 cm, is manually isolated about 40 cm deep; a slope parallel force is manually applied to create slope parallel fractures ("shears") in known or unknown 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.

2.3 Rating the local danger

On each day of field observations, a team of two or three skilled observers traveled on touring skis for at least 15 and sometimes more than 60 minutes to a sheltered site below or at treeline, conducting simple weather, snowpack and avalanche observations as they travelled. At the sheltered site, they recorded the active snowpack observations listed in Table 2. Also at this site, a snow profile was observed and stability tests conducted as described in Jamieson and others (2006). In some cases, the team continued to travel on touring skis above tree line. In addition, they had access to weather, snowpack and avalanche observations from the hosting operation and from neighboring avalanche safety programs. Further, the field observers were working regularly in the area, accumulating their knowledge of the avalanche danger over the winter.

Using all available information, the field team agreed on a danger rating for the local drainage and the current day, called the "local nowcast" (LN). The local ratings of avalanche danger used the same five-level scale and definitions as the regional danger ratings (Canadian Avalanche Association, 2007). In the winter of 2006-07, these local danger ratings were recorded for the treeline elevation band where the forest opens (TL) and

Table 2: Avalanche and snowpack observations

Variable Name	Description	Values	Data type[2]
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	Ordinal (+)
SlabAvRec	Deposit or crown from slab	None, 24 – 48 h old, < 24 h	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 on previous day	Yes, no	Ordinal (+)
Whumpf	Shooting cracks, whumpfs	None, one or more	Ordinal (+)
Crack	Snow surface cracks at skis	None or rarely, common	Ordinal (+)
PinWheel	Pinwheeling (today)	None, one or more	Ordinal (+)
TreeBomb	Snow clumps falling from trees	None, one or more	Ordinal (+)
Drifts	Deposits of drifted snow	None/old, 24-48 h, < 24 h	Ordinal (+)
Scour	Wind scouring/sastrugi	None, one or more affected area/patch	Ordinal (+)
SurfCond	Snow surface condition	Dry fresh, dry settled refrozen crust, wet coarse, sticky, wind affected	Categorical
CrustThick	Thickness of surface crust	cm (0 if no surface crust)	Ratio[1] (+)
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 (+)
HShearR	Hand shear resistance	Easy, moderate, hard, no fracture	Ordinal (-)
HShearDep	Hand shear depth	cm	Ratio[1] (+)
HShearCh	Hand shear character	No planar fracture, resistant planar fracture, sudden planar fracture	Ordinal (+)

[1] Ratio variable but the values were estimated, hence the variable was analyzed as ordinal.
[2] Sign in brackets indicates sign of expected correlation.

Table 3. Weather observations

Variable name	Description	Values	Data type
SnowfallRate	Snowfall rate	0, < 1, 1, 2, 3+ cm/h According to CAA (2007)	Ordinal (+)
WindSpeed	Typical ambient wind speed	Calm, light, moderate, strong/extreme; according to CAA (2007)	Ordinal (+)
SnowBlow	Blowing snow	None, at ridges, below ridges,	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.

below treeline (BTL), provided both could be done with confidence. In the winter of 2007-08, the local danger in the alpine (Alp, above tree line) was also rated if it could be done with confidence.

In most days of winter backcountry recreation, groups ascend through terrain less prone or exposed to avalanches and then make a decision about whether to advance into more exposed avalanche terrain or remain in more sheltered 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 following analyses, we use the combined morning (decision point) and afternoon readings, taking the value which indicates higher avalanche danger.

3. RESULTS

3.1 Distributions of regional and local avalanche danger ratings

The distributions of the regional and local avalanche danger ratings for the 272 cases in this study are shown in Figure 5. While the local danger was rated low or moderate more often than the regional rating, the regional rating was 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, weighting of the regional danger level for specific high use areas within the large forecast regions, and perhaps "erring on the side of caution" by the public avalanche forecasters (Jamieson and others, 2007).

3.2 Correlations of ordinal variables with LN

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 (e.g. Walpole and others, 2007, p. 690-691). Moderate wind speed is often reported to transport more snow into release zones than higher wind speed (e.g. Tremper, 2001, p. 96-97). However, graphs of LN against SnowBlow and WindSpeed (not included) did not show non-monotonic trends, perhaps because we had few observations of strong wind.

Based on Table 4, the following variables correlated equally or more strongly with RF than with LN: LoosAvCur, LoosAvRec, Drifts, SkiPen, SnowfallRate, SnowBlow and Sky. Also, HN24 and HN48 correlated almost as strongly with RF as with LN. Accordingly, these nine variables are not promising for localizing the avalanche danger. The variables SnowfallRate, SnowBlow, Sky, HN24 and HN48 likely reflect regional scale weather processes which are usually well anticipated by regional avalanche forecasters.

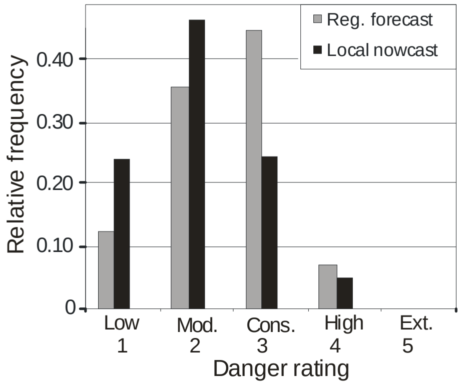

Figure 5: Relative frequencies of regional and local avalanche danger rating.

For localizing the avalanche danger, we selected the ordinal variables which correlate significantly with LN and for which $|R_{LN}| - |R_{RF}| > 0.05$ if R_{RF} is significant, otherwise for which $|R_{LN}| > 0.20$. This rule selects Crack, HShearCh, HShearR, Whumpf and SlabAvRec.

RF exhibited a stronger correlation with LN than any of the field observations, indicating the value of the regional danger rating for assessing the local avalanche danger. Since none of the field observations exhibited a comparable correlation with LN, no single variable is a promising predictor of the local avalanche danger.

3.3 Univariate analysis of a categorical variable

In this section we analyze the categorical variable, SurfCond. The graph in Figure 6 summarizes the LN values for SurfCond. The lowest median value of LN (1) is for a wet coarse-grained surface, whereas it is higher (2-2.5) for the other five classes. Also, there are substantial overlaps between the interquartile ranges for crust, sticky, wind-stiffened and dry fresh. A larger dataset might reveal if wet coarse and perhaps settled snow is usually associated with lower levels of LN. However, with the data available in this study, the snow surface condition does not appear promising for estimating the local danger.

Table 4: Spearman rank correlations of potential predictors with local (LN) and regional avalanche danger ratings (RF).

Potential		LN		RF	
predictor	*n*	R_{LN}	*p*	R_{RF}	*p*
RF	272	**0.46**	10^{-15}	-	-
LoosAvCur	272	-0.06	0.31	**0.16**	0.01
SlabAvCur	272	**0.14**	0.02	0.08	0.19
LoosAvRec	272	0.06	0.31	**0.17**	10^{-3}
SlabAvRec	272	**0.29**	10^{-6}	**0.20**	10^{-3}
Whumpf	272	**0.34**	10^{-8}	**0.18**	10^{-3}
Crack	269	**0.28**	10^{-6}	0.08	0.21
PinWheel	272	0.03	0.59	0.04	0.50
TreeBomb	272	0.01	0.87	0.09	0.14
Drifts	265	**0.22**	10^{-4}	**0.22**	10^{-4}
Scour	272	0.01	0.85	-0.09	0.16
SkiPen	261	**0.18**	10^{-3}	**0.35**	10^{-8}
PoleProbe	272	0.08	0.17	-0.01	0.85
CrustThick	268	0.01	0.89	-0.08	0.19
HShearR	254	**0.22**	10^{-4}	0.01	0.81
HShearDep	226	0.07	0.26	0.09	0.18
HShearCh	191	**0.25**	10^{-3}	0.05	0.51
HN24	223	**0.35**	10^{-7}	**0.32**	10^{-6}
HN48	178	**0.38**	10^{-7}	**0.37**	10^{-7}
SnowfallRate	265	**0.20**	10^{-3}	**0.32**	10^{-7}
WindSpeed	271	0.09	0.13	0.04	0.52
SnowBlow	270	**0.14**	0.03	**0.19**	10^{-3}
Sky	255	**0.14**	0.03	**0.28**	10^{-6}
TempTr24	222	0.05	0.45	0.09	0.20
TempTrTdy	248	-0.06	0.33	0.00	0.96
ReachZero	248	**0.14**	0.03	0.07	0.27
Refreeze	259	0.00	0.99	0.02	0.78

Correlations for which $p < 0.050$ are marked in bold (although at most 2 decimal places are shown in the table).

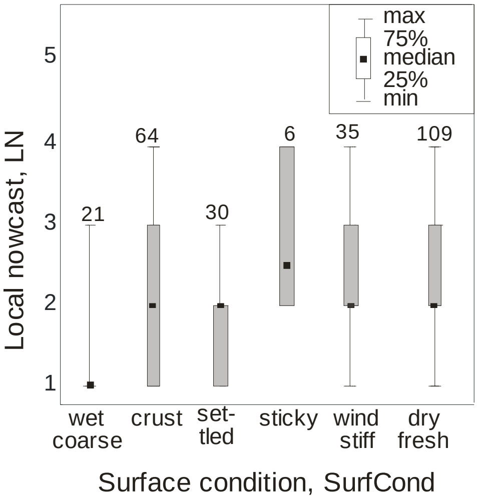

Figure 6: Box and whisker plot of local avalanche danger for six classes of snow surface condition. The numbers of cases is shown above each of the box and whisker plots.

Although the variable Sky is ordinal since it represents increasing cloud cover, the amount of cloud cover may not have a 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. A box plot (not shown) displayed an increasing trend in avalanche danger as cloud cover increased from Few clouds (FEW) to Overcast (OVC). However, the median avalanche danger was higher for Clear sky than for Few clouds. Had more observations been made in the spring when the short wave radiation during the longer days can potentially warm the snow surface more, it is possible that higher danger—especially above treeline—would have been associated with clear sky or few clouds. However, given its weak monotonic trend, we are satisfied with treating Sky as an ordinal variable (Table 4), and with its exclusion as a good predictor for localizing the avalanche danger rating.

4. A MULTI-PREDICTOR MODEL FOR LOCALIZING AVALANCHE DANGER

The objective of this study was to see if selected field observations could be combined with RF to estimate the local avalanche danger, LN. Since RF has the strongest rank correlation with LN, we seek a combination of RF and field observations to yield LN*, which is the output or "predicted" class of LN. The predictors are combined with a classification tree algorithm.

4.1 Classification tree algorithm (CTA)

Given a list of ordinal and categorical variables, classification trees iteratively form splits into two branches by selecting the variable for each split that "best" classifies the response variable. We used discriminant-style splitting in which an analysis of variance (ANOVA), modified for ordinal data, is performed for each predictor at each split and the predictor with the smallest *p*-value selected (StatSoft, 2003). Our response variable was LN. To reduce possible overfitting, we set the minimum node size to 5 cases, which is the default setting in the software we used (StatSoft, 2003). Partly because of the small sample size, we checked that every split in the tree was consistent with experience (e.g. Tremper, 2001, 88-170; McClung and Schaerer, 2006, 197-206).

4.2 Selection of cases

We chose to exclude the 18 cases for which RF = 4 because we wanted to assess a model for RF = 1 to 3 since backcountry travel for non-professional recreationists is not recommended when the danger level in the regional forecast is 4 or 5 (Dennis and Moore, 1996; www.avalanche.ca, 2008). The remaining dataset included 11 cases for which LN = 4 (i.e. LN > RF) but no cases with LN = 5.

4.3 Prior probabilities and misclassification costs

The prior probabilities (priors) are the weights applied to the local danger ratings. If, for example, the Considerable local danger (LN = 3) was weighted highest then the CTA will fit cases within LN = 3 better than less weighted danger levels. The optimal weights would correspond to the most frequent long term local ratings, without any bias towards the operational constraints for data collection or specific conditions during the two winters during which our data were collected. Since long term local ratings we not available, we used relative frequencies of regional danger ratings for 1996 to 2006 (Canadian Avalanche Centre data compiled by Alan Jones, 2006) as summarized in Greene and others (2004); the frequencies for the three vegetation zones were combined. This assumes there is no systematic difference in the frequencies of regional and the rarely available local ratings. Because subsequent sections do not use LN = 5, the priors in Table 5 are normalized without this rating.

Table 5: Relative frequencies of RF and priors

RF	Rel. freq.	Priors[1]	Adj. priors
1	0.16	0.16	0.10
2	0.36	0.37	0.29
3	0.37	0.38	0.45
4	0.10	0.10	0.16
5	0.01	-	-

[1] Priors normalized for RF from 1 to 4

Any simple classification scheme for estimating the local danger will misclassify some of the cases used to build the scheme. However, underestimating the local danger can have higher consequences (costs) than overestimating the local danger. To reduce the frequency of underestimating danger compared to overestimating it, we applied the misclassification costs shown in Table 6. A misclassification cost of 1 is applied to overestimation of the local danger. A cost of 2 or 3 is applied to underestimation of the local danger by one level, or more than one levels, respectively. Misclassification costs can be combined with the prior probabilities to yield adjusted priors (Breiman and others, 1984, p. 114; StatSoft, 2003; Table 5).

Table 6: Misclassification costs

Predicted	Observed LN			
LN*	1	2	3	4
1	-	2	3	3
2	1	-	2	3
3	1	1	-	2
4	1	1	1	-

4.4 Combining predictors

Two hundred and fifty-four cases for which RF ≤ 3 were available from the winters of 2006-07 and 2007-08, as shown in Table 7.

Table 7: Frequency of LN ratings by RF

RF	Observed LN[1]				Total
	1	2	3	4	
1	16 / 16[1]	16 / 16	4 / 4	0 / 0	36 / 36
2	37 / 37	51 / 50	10 / 10	1 / 1	99 / 98
3	11 / 11	58 / 58	42 / 41	8 / 7	119 / 117
Total	65 / 64	129 / 124	65 / 55	13 / 8	254 / 251

[1] Numbers after the slash represent the cases selected for the specific tree.

To maximize the size of the dataset used to build the tree, we used only the highly ranked predictors. There were 251 cases for which RF, RecSlab, Crack and Whumpf were available. HShearR and HShearCh were only available for 236 and 175 cases, respectively, and were not selected by the CTA. The resulting tree is shown in Figure 7. Notably, this tree does not predict LN* = 1, which is a direct result of the adjusted priors used in the analysis. The structure of the tree could be simplified by using OR conditions within IF statements. For example, the left side of the tree could be changed to: IF (Whumpf OR SlabAvRec < 24 h) then LN* = 3 ELSE LN* = 2. On the right side of the tree, the two splits on

SlabAvRec could be changed to a 3-way split. However, our current goal is ***not*** to develop a tree for recreational use, but rather to assess the potential for combining RF with field observations for localizing the avalanche danger.

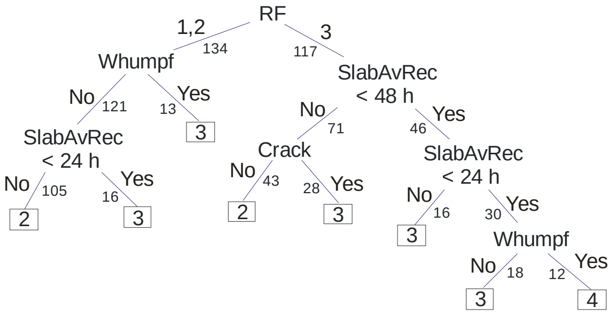

Figure 7: Classification tree for the Columbia Mountains. Output values of LN are in the boxes. Numbers below the branches are the number of cases in the learning sample that take the particular branch.*

Table 8: Classification matrix for tree in Figure 7

Pred. LN*	Observed LN 1	2	3	4	Total
1	0	0	0	0	0
2	55	82	10	1	148
3	9	38	40	4	91
4	0	4	5	3	12
Total	64	124	55	8	251

The classification matrix for this tree is shown in Table 8. With the applied priors and misclassification costs, local danger was correctly classified in 125 cases (50%), over-estimated in 111 cases (44%) and under-estimated in 15 cases (6%). The classification matrix using RF as the predictor for LN for the same 251 cases is shown in Table 7. Using RF only to predict LN*, local danger was correctly classified in 107 cases (43%), over-estimated in 106 cases (42%) and under-estimated in 38 cases (15%). Thus, the classification tree in Figure 7 increased the hit rate by 7 percentage points, decreased the underestimation rate by 9 and increased the overestimation rate by 2 percentage points. (Overestimating the local danger would appear to contribute to conservative decisions but is not desirable, especially in the long term, because recreationists will lose confidence in the ratings and their source.) In view of the improvements in the hit and underestimation rate, an increase of two percentage points in the overestimation rate may be acceptable.

4.5 <u>Summary of combining predictors with a classification tree</u>

- For the first split, the CTA selected RF, which has the highest rank correlation with LN.
- The tree selects SlabAvRec and Whumpf which are regarded as primary indications of instability (e.g. Tremper, 2001, p. 167; McClung and Schaerer, 2006, p. 172-173).
- The tree has some terminal nodes (leaves) with LN* < RF and some with LN* > RF, thus it can rate the local danger higher or lower than the regional danger rating.
- The tree is conservative because we chose higher misclassification costs for under-estimation of local danger than for over-estimation (Table 6). The resulting tree uses more variables since the selected observations are better indications of instability than stability (McClung and Schaerer, 2006, p. 174).
- Symmetric skill score such as the Hanssen-Kuipers discriminant (Wilks, 1995, p. 249) could be used to assess the tree’s output (e.g. Jamieson and others, 2008). However, we prefer to assess the rates of hits, overestimations and underestimations separately because we chose the asymmetric misclassification costs to reduce underestimations of local danger.
- The tree in Figure 7 has not been validated and is not recommended to aid decisions in avalanche terrain. However, we hope the univariate analyses and the tree highlight some important observations for developing a decision aid for the Columbia Mountains.

5. DISCUSSION

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. This is like asking a forecaster: How often are you so surprised by a single observation that you decide to change the danger rating? Informal conversations with forecasters suggest it does happen but is rare.

- Local danger ratings were based on a variety of correlated variables.
- In a related study of snowpack stability tests, Jamieson and others (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.

6. SUMMARY AND CONCLUSIONS

On about 130 location-days in the winters of 2006-07 and 2007-08, a set of 24 potential predictor variables (easy weather, snowpack and avalanche observations) were observed concurrently with local ratings of the avalanche danger in one or more vegetation zones in the Columbia Mountains, yielding 272 records or cases. Of the 23 potential ordinal or ratio predictor variables, 14 exhibited significant rank correlations ($p < 0.05$) with the local avalanche danger. A categorical variable representing the snow surface conditions showed little predictive merit.

We used an established algorithm to construct a classification tree that would have less underestimations of local avalanche danger than overestimations. The tree used the regional danger rating, as well as observations of recent slab avalanches, whumpfs and cracking around skis. Compared to using only the regional danger rating for local rating, the classification tree increased the hit rate by 7 percentage points from 43 to 50%. While the under-estimation rate decreased by 9 percentage points (15% to 6%), overestimation rate increased by 2 percentage points (42 to 44%). This suggests that regional danger rating can be combined with the local observations to estimate the local avalanche danger in the Columbia Mountains. However, we have not validated the model and the preliminary classification tree presented in this study should not be used as a decision aid.

The classification tree is sensitive to the priors and the splitting rule—factors we intend to explore in future analysis of this dataset.

The danger rating from the regional bulletin correlated with the local danger rating better than any of the field observations. This indicates the value of the regional forecasts, even for large regions.

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 and others (2006) analyzed the usefulness and predictive merit of snowpack tests of deeper layers. These tests require digging a pit, are slower and therefore less appealing to some recreationists than the easy observations considered in this paper. However, a future aid for localizing avalanche danger may need to include both types of observations to be effective under a wide variety of snowpack conditions.

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