AUTOMATIC CRUX DETECTION FOR PLANNING BACKCOUNTRY TOURS IN AVALANCHE TERRAIN

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ABSTRACT: For travelling in the backcountry, good planning is crucial. Besides the current weather and avalanche forecast, terrain characteristics must be assessed to identify cruxes in terms of avalanche risk. Nowadays, support is given by slope angle layers and Geographic Information System (GIS) based avalanche terrain maps. When planning a backcountry tour, it is important to draw the route yourself on a detailed map, consider relevant terrain characteristics and define cruxes. To assist in this task, we developed an automatic crux detector. The method automatically identifies potential cruxes from digital avalanche terrain maps and assesses the terrain at these locations in terms of avalanche triggering and the consequences of being caught. In addition, the various associated terrain characteristics are presented. With this information, an initial risk assessment can already be made during the planning phase. Further, this function improves map reading skills in terms of avalanche risk when drawing routes, and it can analyze downloaded GPS tracks to verify the quality of the route and possibly improve it. The automatic crux detection is implemented in the White Risk application. This streamlines the planning process, which finally contributes to safer backcountry tours. In the future, we plan to link the detected potential cruxes to current snow cover conditions.

KEYWORDS: avalanche terrain, crux detection, avalanche hazard mapping, white risk, backcountry tour planning, decision making

1. INTRODUCTION

Winter backcountry touring has become increasingly popular among outdoor enthusiasts. The availability of online resources has made it easier than ever to access information about backcountry tours and tracks, as well as weather and snow information. However, winter backcountry travel inherently carries a certain avalanche risk. It is therefore essential to plan your trip carefully by assessing the avalanche hazard and exposure.

An integral part of trip planning is to check the planned route for potential cruxes, with a particular focus on the main problem at the crux (Harvey and Nigg, 2009).

In this respect, topography plays an important role in identifying the crux and assessing the avalanche risk, as it affects both the probability and the consequences of avalanche release.

Human-triggered avalanches typically release in slightly concave slopes with an average slope angle of 35° (Vontobel et al., 2013). In addition, typical terrain traps such as a concavity at the base of the slope or highly exposed terrain increase the risk.

Unlike the snowpack, the terrain does not change and can be assessed relatively accurately. To take advantage of this, high-resolution digital elevation models provide valuable terrain information. In particular, slope class layers have become standard and are essential for terrain assessment. Moreover, map layers have recently been developed that show the avalanche terrain in all its diversity. For example, Schmudlach and Köhler (2016) or Larsen et al. (2020) have developed a fully automated classification of avalanche terrain based on the Avalanche Terrain Exposure Scale (ATES, Statham et al., 2006).

A different approach was taken by Harvey et al. (2018), who distinguished between avalanche release zones, typical remote triggering areas, avalanche runout zones or the impact of being caught in an avalanche. Using avalanche data and the RAMMS avalanche dynamics model (Christen et al., 2010), two avalanche terrain maps were produced for the entire Swiss Alps and the Jura mountains. These maps were produced from several layers representing important terrain characteristics for assessing avalanche hazard and the associated consequences.

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Our goal here is to automatically detect and classify potential cruxes of a defined route from these avalanche terrain layers.

In this way, potential cruxes can be quickly identified for more detailed analysis. Therefore, avalanche relevant terrain information can be easily included and objectively integrated into the route planning of a backcountry tour. The aim is not to offer pre-determined solutions, but rather to support users in focusing on the essential sections of a planned route. The user should be encouraged to draw his own routes or to modify existing or downloaded routes in order to minimize the number of cruxes encountered.

We used the White Risk tour planning portal as a platform for implementation (www.whiterisk.ch; Harvey et al., 2013).

2. WHAT IS A CRUX?

Broadly speaking, a 'crux' is a pivotal or essential point of a problem or situation, a decisive element that often determines the outcome. In other words, it is the most important part that everything else hinges upon. For winter backcountry touring, the crux is often the section of a route that is most exposed to avalanche danger and where the consequences are the most severe.

In terms of avalanche danger, the slope gradient primarily determines potential cruxes, such as slopes steeper than 30° (steep slopes). In a critical avalanche situation, where spontaneously releasing avalanches or remote triggering are possible, we can also be at risk on terrain below 30°. Cruxes can therefore be defined as follows (Reuter and Semmel, 2018; Harvey et al., 2023):

a) primarily all slopes with an incline of more than 30° (steep slopes, A in Fig. 1).
   Slopes that are clearly favorable in the current avalanche situation may be excluded.

b) if natural avalanches or remote triggering are possible due to a critical avalanche situation, the terrain below steep slopes or the runout area of medium sized or even large avalanches should also be considered as crux (B1 and B2 in Fig. 1).

In most cases, where the snowpack is not very unstable, steep slopes (>30°) and areas at the base near steep slopes are relevant for the assessment. We have focused on this type of terrain (yellow marked section in Fig. 1). If the avalanche situation is very unstable – such that natural or widespread remote triggered avalanches are expected – the avalanche terrain, including runout areas, should generally be avoided (C in Fig. 1). For this purpose, avalanche terrain maps that include release and runout areas are ideal. Just stay out of these defined areas when drawing the route.

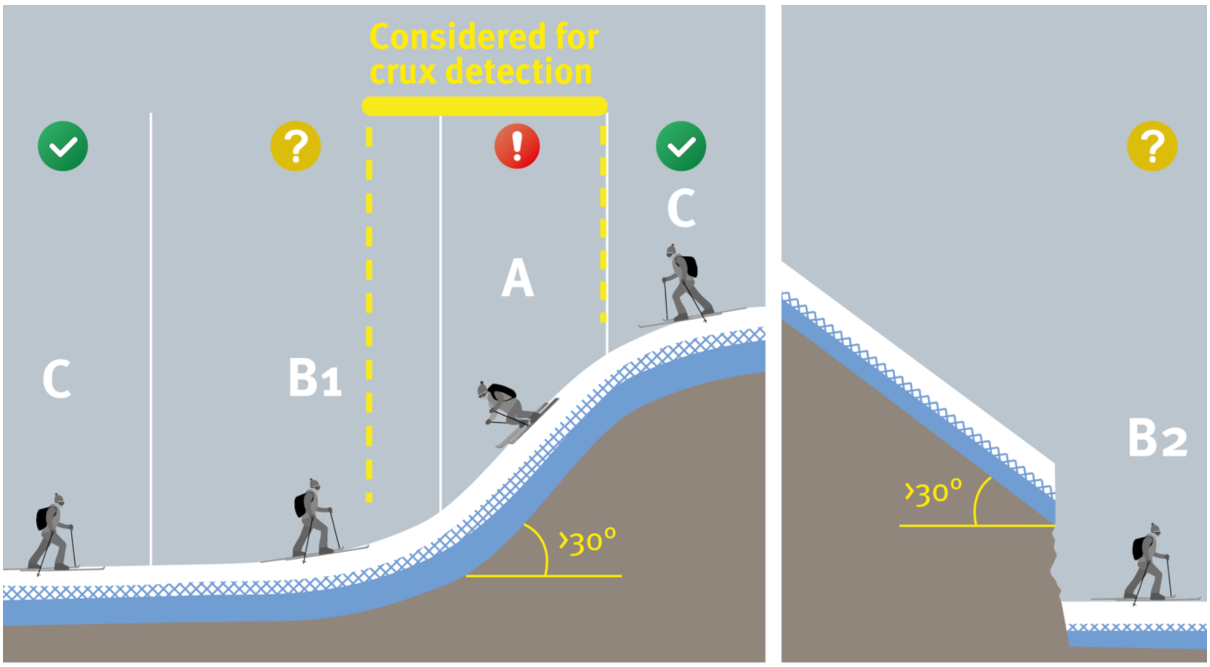

Figure 1: Steep slopes (A) are the most frequent cruxes. In critical situations, we can also be at risk in less steep terrain (B). At the sites C there is, under normal circumstances, no risk. They then can be considered as safe locations. The yellow marked area shows the zones taken into account for automatic detection (adapted from Harvey et al., 2023).

3. METHODOLOGY

For planning a backcountry tour, the severity of the terrain in terms of avalanche risk is indicated by the ***a**valanche **t**errain **h**azard* map (ATH) developed by Harvey et al. (2018). It considers the terrain in terms of a) its characteristics for a possible avalanche release and b) the potential consequences of being caught. The hazard is indicated between 0 and 1. This map layer formed the basis for the crux calculation. At first, we estimated a terrain-related "triggering probability" at a given location for an avalanche that could seriously endanger people. Therefore, we analyzed 300 accidental avalanches and examined the position of the skiers or snowboarders when the avalanche was triggered. At these locations, we identified the six highest values from the "ATH" layer. The values of these pixels were considered for the trigger location.

We then calculated a density distribution of these values and made a correction by dividing the density estimates by the base rate density of the same layer from the Swiss Alps. This was to reduce the bias of the possibly unbalanced accident data and to obtain a density relative to the base rate. Finally, the cumulative frequency distribution of this relative density was used to determine a terrain-related "trigger probability" (Fig. 2), hereafter referred to as "trigger probability terrain" (TPT). For a given cell value, this probability was determined from the fitted curve in Fig. 2 as follows:

$P(cell) = x^{3.5}$,

where x is the cell value of the "ATH" map layer.

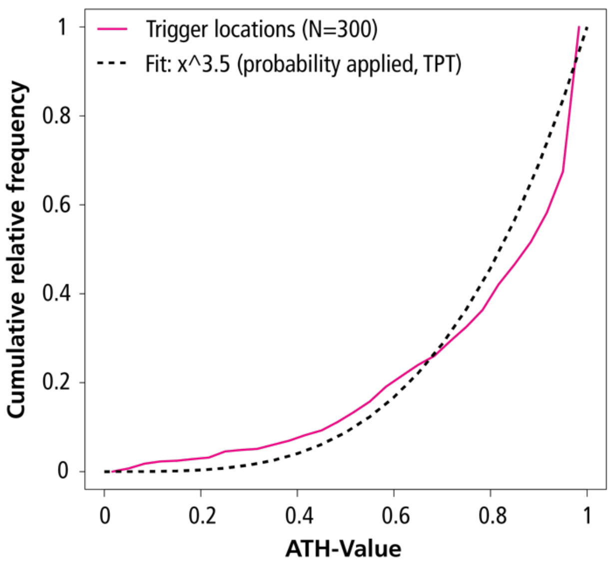

Figure 2: Relative cumulative distribution of ATH values at approximate trigger locations (six highest values) of 300 accidental human-triggered avalanches (red line). The dotted line shows the fitted curve which was applied in the crux calculation.

This approximated probability only takes into account the terrain regardless of the snowpack stability or the amount of snow released. It only serves to compare terrain characteristics with regard to the triggering locations of accidental avalanches. The effective triggering probability depends, of course, to a large extent on the current snowpack stability.

3.1 Calculation of the crux

Within a moving window of 40 meters along a route line, we calculated a trigger probability (TPT) for passing through all the cells ($P(window)$) using Eq. 1.

We took the ATH layer values at six points spaced along the route within this moving window. The distance between the points was therefore 8 meters (Fig. 3). With these six values Eq. 1 was calculated for each moving window.

$$P(window) = 1 - \prod_{i=1}^{6}(1 - x^{3.5}) \qquad \text{(Eq. 1)},$$

where x is the ATH map values from each of the six points within the moving window.

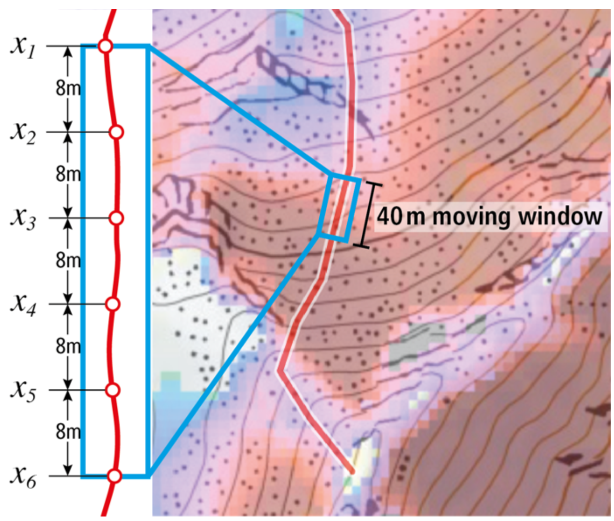

Figure 3: Extracting the cell values of the "ATH" map layer within the moving window of 40 meters along the route.

The higher $P(window)$, the more likely an avalanche can be triggered at this location, taking into account only the given terrain characteristics. Values above 0.35 were considered as crux and classified as such (see Fig. 4, Chapter 4).

3.2 Remote triggering and danger of falling

Locations right at the base of steep slopes have a particular potential for remote triggering at rather unstable snowpack conditions. The crux calculation often remains below the threshold mentioned above to be listed as a crux at such locations. In order to include the base near avalanche prone slopes, a second calculation was performed using the same equation Eq. 1, but with twice the window size and correspondingly more points. A different map layer was used representing the release and remote trigger potential. Here, values of $P(window)$ above 0.2 were considered as cruxes and marked accordingly (see Fig. 5, Chapter 4).

Routes that pass through terrain steeper than 50° were excluded from the calculation. These zones are highly dangerous fall areas and are marked as such.

4. IMPLEMENTATION IN WHITE RISK

The automatic crux detection is integrated in the tour planning module of the White Risk application (www.whiterisk.ch and mobile app). It can be switched on and off manually for each planned route individually.

If the $P(window)$ value (Eq. 1) reaches one of the defined threshold values, this location is marked as a crux and delineated with a yellow thick line. It is then categorized depending on the threshold. Symbols with exclamation marks classify the crux into one of four classes, determined by the magnitude of $P(window)$. The more exclamation marks, the higher $P(window)$ and the more unfavorable the avalanche terrain. Cruxes with three exclamations marks are pronounced avalanche terrain and require a favorable avalanche situation. If the three exclamation marks are red, they indicate the upper edge of the avalanche terrain hazard. At each identified crux, the slope, aspect and elevation are displayed in addition to the potential avalanche terrain hazard (Fig. 4).

Figure 4: Classification of the automatically detected cruxes in the White Risk application according to level of terrain hazard.

Beyond the exclamation marks, there are symbols indicating an elevated potential for remote triggering or a danger of fall (Fig. 5). To illustrate the increased potential for remote triggering, a map layer was used that represents the terrain characteristics prone to such events. Slopes greater than 50° are designated as fall terrain.

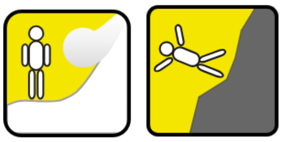

Figure 5: Crux symbols indicating an increased potential of remote triggering (left) and danger of fall (right).

Clicking on an icon displays additional information about the release and trigger potential, as well as possible consequences (see Fig. 6).

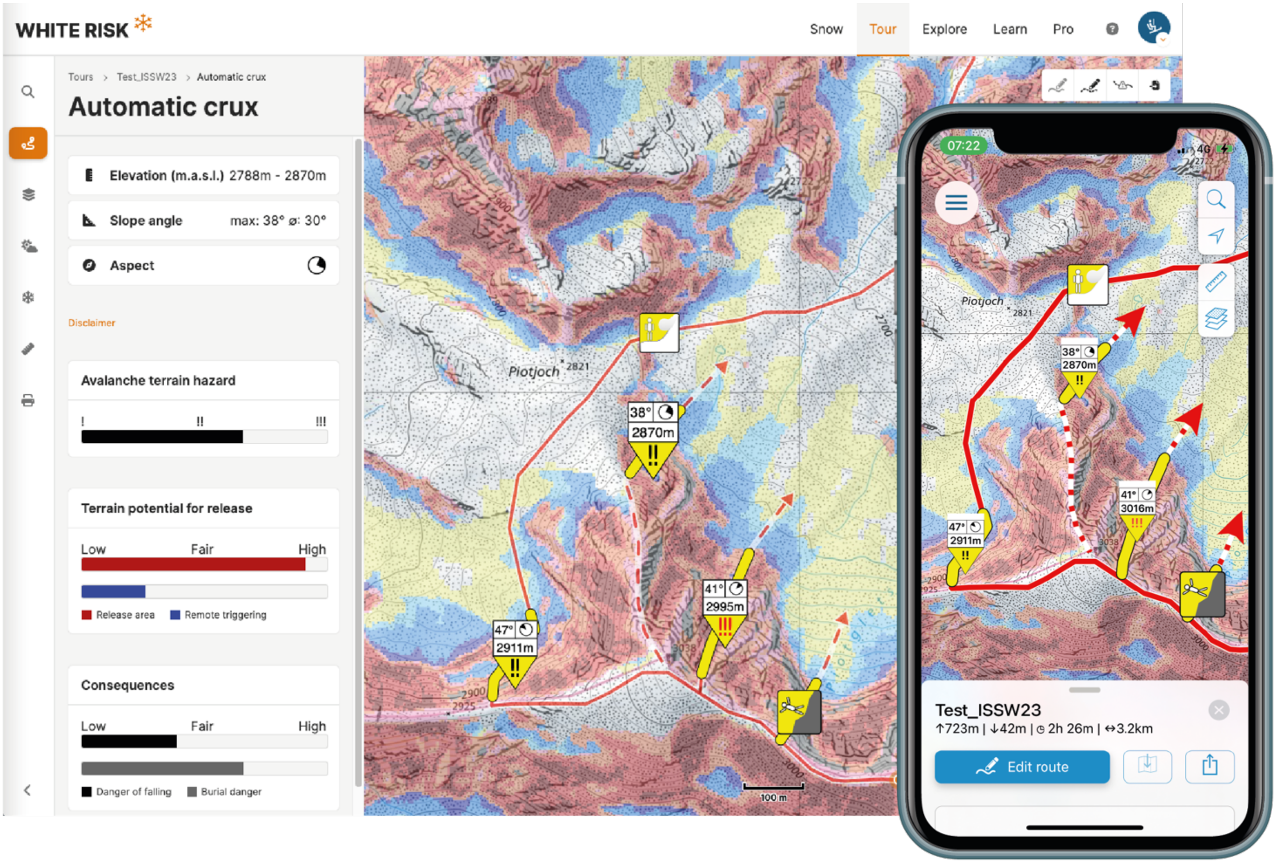

Figure 6: Example of automatically detected cruxes. The icon at each crux indicates its characteristic and severity level. The large image represents the web version (www.whiterisk.ch), while the smaller one simultaneously shows the same crux within the app White Risk. If the route is changed, constant recalculations and synchronization are done. Clicking on a crux reveals additional information, such as an indication how likely the terrain characteristics favour avalanche release, or the type and severity of possible consequences. The underlaying map shows the classified avalanche terrain map layer which distinguishes between avalanche release area, areas with potential for remote triggering and runout zones of size 3 avalanches.

5. DISCUSSION

Our objective was to create an automated system to identify potential cruxes during the planning of backcountry tours considering avalanche terrain. To achieve this, we developed a methodology capable of identifying cruxes, assessing their severity, and providing detailed information based on the avalanche terrain characteristics. For each identified crux, essential details regarding avalanche release and potential consequences of being caught, potentially resulting in severe injury or burial risks, are presented.

These detected locations demand special attention when assessing the risk, as they can significantly impact tour safety. Incorporating terrain details for each crux has led to a valuable tool for planning backcountry tours, selecting routes and for risk assessment.

Our methodology has been successfully implemented in the tour planning tool of White Risk. Whenever a route is drawn or GPS tracks are imported, the cruxes are automatically displayed. This dynamic feature allows continuous adjustments to the route until the fewest possible cruxes are highlighted. Such real-time feedback substantially improves avalanche terrain analysis and enhances quality of a self-drawn route as well as map reading skills. The classification of the crux and the detailed terrain information provides valuable input for the risk assessment at the crux. Moreover, the automated crux identification aligns well with the intuitive judgment of experienced backcountry recreationists and mountain guides.

Nevertheless, this tool has its limitations. The accuracy of the underlying map layers is one such limitation. Although great care has been taken to produce the avalanche terrain maps, they are based on avalanche data, digital terrain models and numerical simulations, making it difficult to precisely represent reality. In addition, these maps are based on avalanche events with a short return period and a maximum avalanche size of class 3. Consequently, potential cruxes in the runout zone may not be identified when larger avalanches are expected, typically associated with danger level 4 situations (high).

It is also important to note that the automatic crux detection only considers terrain and does not take into account the current avalanche situation or technical difficulties. These factors, in addition to terrain, are very important for assessing the risk. Last but not least, human factors can also significantly influence the risk at certain cruxes.

6. CONCLUSION AND OUTLOOK

When planning a backcountry tour at home, or when making decisions at the individual slope, evaluating the severity of the terrain with regard to avalanche risk is crucial. The automatic crux detection presented here is a valuable tool for analyzing different characteristics of avalanche terrain at the most relevant sections of a route, especially when planning a backcountry tour. The tool helps to focus on potentially avalanche prone terrain for the most relevant sections. At each crux, important terrain information is available, supporting a crux specific risk analysis. However, the tool is intended primarily for planning purposes and only for avalanches up to and including size class 3. The presented tool is currently available for the Swiss Alps and the Jura mountains within the White Risk tour planning module. It can be implemented for other countries when the necessary avalanche terrain layers are available.

The next steps include improvements to the map layers and the integration of current snow and avalanche information. Thus, an approximate avalanche risk, considering trigger probability and consequences as described by Reuter and Semmel, (2018), Harvey et al. (2018b) and Harvey et al. (2023), could be automatically assessed in real-time at each detected crux for a self-drawn or adapted route.

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