PRACTICAL METHODS FOR USING VEGETATION PATTERNS TO ESTIMATE AVALANCHE FREQUENCY AND MAGNITUDE

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ABSTRACT: Practitioners working in avalanche terrain can benefit from learning about and characterizing the avalanche paths that they are dealing with. A worker may never witness an extreme event, but understanding extreme events is important for categorizing avalanches that occur within a given season. Historical records of avalanche incidents and direct observations are the most reliable evidence of avalanche activity, but patterns in vegetation can be used to further quantify and map the frequency and magnitude of past events. We surveyed published literature to evaluate approaches for using vegetation sampling to characterize avalanche terrain to identify the benefits and caveats of using different practical field methods to estimate avalanche frequency and magnitude. Powerful avalanches can deposit massive piles of snow, rocks, and woody debris in runout zones. Large avalanches (relative to the path) can cut fresh trimlines, widening their tracks by uprooting, stripping, and breaking trees. Discs and cores can be collected from downed trees to detect signals of past avalanche disturbance recorded in woody plant tissue. Signals of disturbance events recorded in tree rings can include direct impact scars from the moving snow and wind blast, development of reaction wood in response to tilting, and abrupt variation in the relative width of annual growth rings. The relative ages of trees in avalanche paths and the surrounding landscape can be an indicator of the area impacted by past avalanches. Repeat photography can also be useful to track changes in vegetation over time. We conclude that several vegetation ecology methods can be used in combination to characterize local avalanche frequency.

KEYWORDS:
snow avalanche path vegetation, plant species diversity, tree-ring analyses, disturbance ecology

1. INTRODUCTION

Avalanches and vegetation

Snow avalanches are an important disturbance process in many subalpine forest ecosystems (Bebi et al., 2009), and they can also be a major natural hazard, threatening life and property in mountainous areas (McClung and Schaerer, 2006). The snow avalanche process is highly variable in terms of size, material properties, and behavior (Mears, 1992). Avalanche formation is the result of a complex interaction between terrain, snowpack, and meteorological conditions leading to avalanching (Schweizer et al., 2003).

An avalanche path (Martinelli, 1974) refers to an area where a mass of snow moves rapidly down a slope, including the starting zone, where unstable snow releases, the track that is impacted by the moving snow and powder blast, and the runout zone where debris is deposited. The frequency of avalanching in a path area may vary from several times per year, to as low as once per three hundred years or more (Mears, 1992). Also, the frequency may be high in the upper portion of a path but generally decrease lower in the runout zone (McClung and Schaerer, 2006). For example, several small slides may occur each winter in the starting zone of the upper portion of an avalanche path, while a very large slide can potentially run the full extent of the path, and flow out over the runout zone. A large, high-magnitude avalanche may be capable of redefining the areal extent and

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topographic parameters of a path (Luckman, 1977; McClung and Schaerer, 2006).

Avalanches can damage or kill individual trees and forests that are located in vulnerable topographic settings (Burrows and Burrows, 1976). Areas of frequent avalanche activity often appear as vertical swaths of open vegetation down steep mountain slopes, characterized by a different type or age of the dominant vegetation, or a lack of vegetation (Mears, 1992; Patten and Knight, 1994; Butler, 2001; McClung, 2003; Walsh et al., 2004).

While avalanches can affect forest ecosystems through vegetation damage, the forest conditions can also influence the frequency and magnitude of avalanches (Bebi et al., 2001; Sakals et al., 2006; Bebi et al., 2009). A dense stand of trees can affect the likelihood of avalanches starting, potentially protecting large areas of human settlement and infrastructure (Gubler and Rychetnik, 1991). Live and dead tree stems may increase surface roughness and anchoring, and forest vegetation can shelter avalanche-prone slopes, slowing the redistribution of snow due to wind and shading the snow surface from solar radiation (McClung and Schaerer, 2006).

However, many avalanches occur high above treeline in steep alpine terrain. Once a snow slide is initiated, the mass of moving snow can mobilize anything in its path. Forested areas near the alpine treeline, and in close proximity to starting zones, may be more important as protection forests than forests lower in the track or runout zones (Gubler and Rychetnik, 1991; Bebi et al., 2001; Mears, 2006).

The force of wind blasts often associated with large dry powder avalanches can also result in stem breakage, damage to branches and roots, and disruption of tree growth (Burrows and Burrows, 1976; Mears, 1992). During an avalanche large enough to destroy established trees, damage is not limited to the direct impacts of the moving snow and wind blast. Broken trees and rocks from higher up the slope can become entrained in the moving snow and debris (Mears, 1992; Weir, 2002). These can scar and damage vegetation lower in the path, scour soil, uproot trees, and deposit massive piles of ice, snow, rocks, soil, and woody debris in runout zones. Rocks may be found lodged in the branches of trees along path margins.

Not all snow slides will damage the vegetation (Mears, 1992; Weir, 2002). When the snowpack is deep enough to cover the plants or trees, they can be protected from the moving snow and debris. Low-density, dry-snow, or powder avalanches can flow through open, dispersed forests, but may contain enough energy to damage structures, such as buildings with large exposed areas. Some snow slides are mostly limited to redistribution of the snow cover, which can result in changes in the timing and availability of moisture and nutrients that are needed for plant growth.

In addition to the physical damage from avalanche impacts, plants can also respond to changing environmental conditions resulting from the vegetation disturbance, such as higher levels of light, moisture, and nutrients, and opportunities for seedling establishment (Stohlgren, 2007). Avalanche disturbances create a diverse vegetation mosaic on the landscape (Patten and Knight, 1994; Kulakowski et al., 2006), and avalanche paths support unique habitats and a high diversity of plants and animals in subalpine and alpine areas (Rixen et al., 2007).

2. METHODS

Avalanche Path Vegetation Methods

Documented observations of avalanche events provide the most reliable information, but historic records are often incomplete or strongly influenced by patterns of human activity in an area (Armstrong and Armstrong, 2006). Tree-ring and vegetation analyses can be used to improve the dating of past avalanches and estimate the frequency and intensity of snow slide events for specific avalanche path locations and time periods of interest (Burrows and Burrows, 1976; Carrara, 1979; Mears, 1992; Jenkins and Hebertson, 2004; Casteller et al., 2007; Butler and Sawyer, 2008; Reardon et al., 2008; Bebi et al., 2009). Common approaches include the use of vegetative indicators, analysis of tree rings, and repeat photography analysis.

Vegetative Indicators

The margins of forested areas along the width of an avalanche path are often referred to as trimlines (Burrows and Burrows, 1976). On certain slopes the avalanche path trimlines are conspicuous, discrete boundaries (e.g., an area of dense forest bordered by an open meadow or confined gully; Luckman, 1977). Clearly defined trimlines can result from frequent avalanches or an exceptional event that has cut a swath into established forest (Burrows and Burrows, 1976). They may still be fairly obvious when the transition is from a conifer to a deciduous forest, or from older to younger trees of the same species (Mears, 1976; Mears, 1992). However, in some areas the vegetation transitions between avalanche paths and the surrounding landscape are relatively continuous, and may be better described as gradients, or mosaics that are changing through time (Stohlgren, 2007).

Where avalanches occur with sufficient frequency, mature coniferous forest species may be precluded from successfully establishing (Johnson, 1987; Patten and Knight, 1994). These paths are often vegetated by deciduous tree species with flexible stems (e.g., *Alnus*, *Acer*, *Betula*, and *Populus* species), as well as a variety of shrubs, grasses, and herbs.

Avalanches typically result in vegetation that is characterized by smaller and shorter trees, lower stem densities, and greater structural diversity, compared to unaffected areas nearby (Bebi et al., 2009). Stems may grow in a tilted position, typically pointing downslope in the direction of avalanche flow, and "J" shaped trunks may develop in response to repeated impacts and tilting (Weir, 2002).

When assessing vegetative indicators of avalanche frequency, it may be useful to consider that the probability of breakage and uprooting is not the same for all vegetation types and sizes (Johnson, 1987). Stem size and flexibility, along with the spatial position of the tree relative to the avalanche, are important factors influencing the damage that an individual tree will sustain (Bebi et al., 2009). Stems of smaller trees and shrubs may be flexible enough to bend or lean without breakage. Increased susceptibility to breakage in common subalpine tree species has been reported for stem diameters > 6cm, and critical diameters can be higher for deciduous tree species with more flexible stems (Mears, 1976; Johnson, 1987). In trees with larger diameters, the stresses exerted by avalanches can exceed the strength, resulting in bole breakage or uprooting if the avalanche pressure is high enough (Johnson, 1987; Mears, 1992; Weir, 2002; Bebi et al., 2009).

Where snow avalanche records are not available, vegetative clues may be useful in estimating the avalanche frequency (see Table 1; Mears, 1992; Weir, 2002; McClung and Schaerer, 2006). Vegetation indicators have been described generally for different avalanche return intervals, and specific plant species or assemblages may also be valuable as indicators of frequency for individual path locations. The return period indicates a frequency of at least one large avalanche in the time interval.

Table 1: Vegetation as an avalanche frequency indicator (After Mears, 1992).

Return period	Vegetation Indicators
1-10 years:	Track supports grasses, shrubs, and flexible species (e.g., alder and willow). Patches of bare soil may be present, no trees higher than 1-2 m. No dead wood from large trees except at edges or end of runout zone.
10-30 years:	Predominantly pioneer species. Dense growth of small trees and young trees similar to adjacent forest. Broken timber on ground at path boundaries. Increment core data may be useful.
30-100 years:	Mature pioneering species of uniform age (e.g., non-coniferous), and young trees of conifer species, old and partially decomposed debris. Increment core data useful.
More than 100 years:	Mature, uniform-age trees of climax species. Increment core data may be required.

A major caveat for using vegetative indicators is that plant species distributions are influenced by many factors other than avalanches. Landscape legacies, past disturbance events, and initial timing of plant establishment can have a strong influence on forest structure and conditions, making observed patterns difficult to interpret (Veblen et al., 1994; Stohlgren, 2007).

Tree-ring analysis

The use of dendro-chronological evidence to evaluate snow avalanche activity has been reviewed many times, ranging from the classic manual of Burrows and Burrows (1976) and the avalanche practitioner's guide to techniques by Jenkins and Hebertson (2004), to the most recent papers (Butler and Sawyer, 2008; Casteller et al., 2007; Stoffel and Bollschweiler, 2008; Luckman, 2010).

Avalanche dating techniques using dendrochronology and vegetative analysis are based on the concept that vegetation growing along the trimlines and within the run-out zone of an avalanche path is likely to experience damage resulting from the impact of snow and debris (Jenkins and Hebertson, 2004). Development of reaction wood in response to tilting (visible as darker growth tissue and eccentric rings), recovery from impact scars, and abrupt changes in annual growth (as recorded in the tree rings) can occur in the years following an avalanche disturbance (Casteller et al., 2007; Reardon et al., 2008).

Typically, in the middle of an active avalanche path, growth rings are relatively narrow, due to the stress of repeated avalanche damage (Burrows and Burrows, 1976). In contrast, the sole surviving tree in a fresh trimline area would be expected to have larger rings for several years following the event, indicating a period of increased growth due to the release from competition, and the increased availability of light and nutrients.

Extracting and analyzing increment cores from trees can be a useful method for estimating avalanche frequency, particularly at locations of long return-period avalanching (Mears, 1992). Tree ages sampled within suspected boundaries of avalanche paths can also be compared with those outside the boundaries to estimate the area impacted by past avalanches (Casteller et al., 2007). When avalanches occur more frequently than once in 10 years, tree-ring analysis is difficult to interpret, and so the heights of the vegetation (e.g., shrubs such as willows, and small trees) may provide simple clues about frequency (McClung and Schaerer, 2006).

One of the major caveats of tree ring analysis is that all none of the disturbance signals are completely specific to avalanches. The main approach to dealing with this problem has been to learn as much as possible about the effects of avalanches on vegetation, in order to better isolate the signals from other disturbances. Recent progress has been made in differentiating avalanche disturbance from landslides (Szymczak et al., 2010), and rockfall (Stoffel et al., 2006). Investigators have addressed this problem through detailed protocols for sample collection, and they have also used multiple dendrochronological approaches in combination, to improve reconstructions of past avalanches (Mears, 1992; Casteller et al., 2007; Butler and Sawyer, 2008; Reardon et al., 2008). However, in many subalpine forest areas it will not be realistic to isolate avalanches from other disturbances. Multiple, interacting disturbances (ranging from fire and insect outbreaks, to human activities) may have important effects on the vegetation conditions in avalanche paths (Veblen et al., 1994; Kulakowski et al., 2003; Kulakowski et al., 2006).

Samples collected from different heights or positions on a tree may not contain the same signals (Stoffel et al., 2006). Cross section samples collected close to the root buttress may provide more reliable dates for tree establishment and development of reaction wood, but in general, disturbance samples should be collected at the scar or area of direct impact (Reardon et al., 2008). When collecting increment cores from scarred trees, it is important to sample just to the side of the scar, so that the complete record of growth rings formed following the damage will be included in the sample (Stoffel and Bollschweiler, 2008).

Although it may be possible to date individual impact scars, many applications of dendrochronology require adequate sample sizes and rigorous statistical analyses (Butler and Sawyer, 2008). Discs and cores can be collected relatively quickly, but the processing of samples can involve substantial time and expense (Pederson et al., 2006). If time permits, plan to collect additional samples from trees nearby, and in different areas of the path, to increase sample sizes and extend the local chronology. In addition to sampling trees at the path margins and trimlines, consider collecting samples from trees in areas both on and off paths, areas of scattered trees, shrubs, or sparse woody vegetation, debris piles, and unaffected or very infrequent avalanche areas.

Tree ring samples with multiple signals of avalanche disturbance are the most reliable. A rating system with 5 different categories for avalanche-induced growth responses (as they are recorded in tree rings) has been developed (Table 2; Pederson et al., 2006; Reardon et al., 2008). This system for categorization can allow for filtering of data by sample quality during analysis.

Table 2: Ratings for Avalanche Samples (After Reardon et al., 2008)

1	Clear impact scar associated with obvious reaction wood or growth suppression.
2	Clear scar, but no reaction wood or suppression of growth, or, obvious reaction wood/suppression of growth that occurs abruptly after complacent, or Clear scar, but no reaction wood or suppression of growth, or, obvious reaction wood/suppression of growth that occurs abruptly after complacent, or "normal" growth, and that lasts for approximately 3 years.
3	Well-defined reaction wood/ suppression of growth, but only prevalent in 1 or 2 successive growth years.
4	Reaction wood or growth suppression present but not well-defined, or reaction wood present but formed when tree was young, and more susceptible to damage from various environmental and biological conditions.
5	Same as (4), except reaction wood is very poorly defined, and slow onset may indicate other processes such as soil or snow creep may be primary causes.

Guidelines for Common Practice

The following guidelines represent a series of approaches and initial steps that an avalanche practitioner might want to consider when embarking on an investigation of avalanche path vegetation. Depending on the specific questions, certain approaches may be more or less appropriate for practical application.

Avalanche Path Vegetation Methods

1) Identify potential avalanche areas.
Use maps and photos (including aerial photos and other available images) to identify path boundaries and estimate path dimensions, based on locations of past avalanche observations, potential starting zones, terrain features, and vegetation cover (Mears,1992; Atkins, 2001; McCollister and Birkeland, 2006; Scott, 2007; Greene et al., 2009).

2) Compile a chronology of known avalanche events for the area.
Gather information on past avalanche incidents from literature, accident reports, personal interviews, photographs, newspaper articles, and other reliable sources (Armstrong and Armstrong, 2006; Reardon et al., 2008).

3) Survey for evidence of disturbance.
Locate areas of recent vegetation damage in the avalanche path, including fresh trimlines, debris piles, uprooted trees, scarred stems, broken branches, and other signs of disturbance (Burrows and Burrows, 1976). Fallen trees and tilted stems may be aligned in the direction of avalanche flow. Branches may be stripped from the upslope sides of trees. In addition to avalanche width, the flow heights and runout distances of avalanches can sometimes be estimated from vegetation damage, such as the heights of tree branch breakage, scars on the uphill sides of trunks, and locations of debris in runout zones (Mears, 1975; Mears, 1992).

4) Collect tree-ring samples from trees that have been damaged by avalanche.
Remove cross sections of dead, downed trees, if this is permitted, and the conditions are safe for saw work (Burrows and Burrows, 1976; Jenkins and Hebertson, 2004; Reardon et al., 2008). Use an increment borer to collect cores of scarred, broken, or stripped trees. Cross sections from the dead leaders of avalanche damaged (living) trees may also provide high quality samples (Reardon et al., 2008). Start with broken and uprooted trees that are found *in situ*, and record the location of each sampled tree. If time allows, collect additional increment cores from several locations on scarred and broken trees, from trees nearby, and from trees in other locations on and off the path.

5) Map areas of debris
Survey the runout zone, trimlines, and path for areas of persistent snow, woody debris, rocks, and broken vegetation. Map perimeters of fresh trimlines, and locations of downed or broken trees. Measure the height and extent of woody debris deposited along path margins and in runout zones (Burrows and Burrows, 1976).

6) Vegetation structure and diversity
Forest monitoring plots and vegetation surveys can be used to assess patterns of species diversity and disturbance (Stohlgren, 2007). Measurements of forest and alpine plant species distributions may not be feasible for an initial avalanche path investigation. However, datasets may available for the path or areas nearby, ranging from forest monitoring plots to detailed plant species inventories. Surveys of vegetation in avalanche paths could be focused on the dominant cover types, height of vegetation, density of trees, and structural diversity, depending on available resources.

7) Calculate avalanche path parameters
Use terrain features and vegetation signals to improve estimates of maximum runout zones, avalanche velocities, and impact pressures, inferred from characteristics of the terrain, trees broken by the moving snow and wind blast, and other indicators of vegetation disturbance. Height of broken branches may provide one estimate of flow height, and powder blast probably exceeds the height of limb damage (Mears, 1975; Mears, 1992).

An increasing area of interest is the investigation of large avalanche events (Logan and Williams, 2005; Sharaf et al., 2008; Erich Peitzsch, US Geological Survey, Northern Rocky Mountain Science Center, personal communication, 2010). Large avalanche events can provide unique opportunities to use patterns of vegetation structure and damage in evaluating the potential “extreme runout” in space and time (Butler and Sawyer, 2008). Information on past avalanche return intervals and extreme runout distances can be useful in evaluating and categorizing an observed avalanche event. For example, snow safety personnel may be interested in knowing whether a major avalanche event has reached a particular area of interest within the last 100 years (Jenkins and Hebertson, 2004).

8) Monitor the path using photography
Repeat photography analysis can be valuable in identifying changes in the boundaries of avalanche paths and vegetation cover in avalanche terrain (Mears, 1992). Aerial photographs, maps, and remote sensing images may also be useful in tracking vegetation conditions in starting zones, near treeline, and in alpine areas (Walsh et al., 2004).

4. CONCLUSIONS

Interactions of snow avalanches and vegetation depend on the terrain features, size of avalanches, type of snow, and other important factors. Direct observations will always be the most reliable evidence of the occurrence of snow avalanches. However, measurements of vegetation can be useful in improving and extending the historical avalanche record at a site. Vegetative indicators of avalanche frequency can include patterns of forest cover, vegetation structure, plant species diversity, vegetation damage and disturbance, and plant regrowth and recovery. Tree ring analyses have proven very useful in improving records of past avalanche activity. Impact scars and characteristic damage to woody plants from the moving snow and associated wind blast provide the most direct evidence of snow slide activity. Multiple indirect signals of dendro-ecological disturbance can also be used to estimate the local geography of past snow avalanches. Valuable indicators can include abrupt changes in the relative width of annual growth rings, development of reaction wood in response to tilting, and evidence of physiological stress such as the presence of traumatic resin ducts. Dates and areas impacted by avalanche events can sometimes be identified using single indicators, but reconstructions of past avalanche activity can almost always be improved through the combination of several approaches. The selection of appropriate methods for investigation of an avalanche path will depend on characteristics of the local terrain and vegetation, the nature of the avalanche hazard, the questions of interest, and available resources.

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