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Snow Avalanches and Vegetation Pattern in Cascade Canyon, Grand Teton National Park, Wyoming, U.S.A.

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Abstract

Snow avalanches in Cascade Canyon, Grand Teton National Park, have a significant effect on the region's vegetation mosaic, increasing the area's community diversity and creating a fragmented vegetation pattern. The structure and persistence of communities within avalanche tracks is a function of the frequency of avalanche occurrence. In many areas, shrub cover and conifer density increase as avalanche frequency increases. Conifers decrease in size yet increase in age as avalanches occur more often, a consequence of slower growth rates in trees within avalanche tracks. Because the probability of avalanche damage to conifers is related to the size of the tree, slow growth rates result in small trees that can survive many years in avalanche tracks, contributing to the persistence of the avalanche community. The canyon's vegetation patterns appear fairly stable due to the spatial and temporal consistency of avalanche occurrence and the persistence of communities in avalanche tracks. The primary effect avalanches have on this landscape is to increase the fragmentation of the vegetation patterns rather than to drive dynamic changes in the landscape mosaic.

Introduction

The vegetation mosaic of many landscapes is a function of the existing disturbance regime, with the frequency, size, and location of events influencing the structure and distribution of communities (Pickett and Thompson, 1978; Shugart and West, 1981). The effect of disturbance on vegetation patterns is demonstrated in the Rocky Mountains, where snow avalanches are a common phenomenon. Their frequent occurrence can play a significant role in structuring the mosaic of mountain landscapes (Khapayev, 1978; Butler, 1979, 1988; Cushman, 1981; Johnson, 1987).

This study was designed to determine how snow avalanches can influence both the patterns and dynamics of mountain vegetation by studying a section of Wyoming's Grand Teton Range (Fig. 1), an area where the complex vegetation mosaic appears to be related to snow avalanche occurrence. Analyses examined the impact of avalanches on three aspects of Cascade Canyon's vegetation: community distributions, woody components of avalanche communities, and landscape patterns. Vegetation maps were used to examine the relationship between community distributions and avalanche occurrence. Data on shrub and conifer abundance provided information on the impact of avalanche on woody components of the community. Tree growth rates and observed avalanche damage were used to analyze whether avalanche communities are persistent, forming a disclimax due to recurrent disturbance. Observations of the effects of destructive avalanches that occurred outside of their normal pattern of flow were used to assess if this disturbance type results in long-term changes in the existing landscape patterns.

Study Area

The study area was located in the central portion of Grand Teton National Park in northwest Wyoming, within Cascade Canyon (Fig. 1). Elevation of the canyon floor ranges from approximately 2195 m at the mouth to 2255 m at the far western end. The south-facing slope is rocky and dry with bare cliffs starting around 2560 m. The north-facing slope is more mesic, with vegetation extending to higher elevations. Sampling was only feasible up to 2740 m on this slope due to the extreme topography. Some data were also collected north of Cascade Canyon, at an avalanche track near Laurel Lake (Fig. 1).

Methods

Data for community classification were collected in the summer of 1985 from 110 stands spread throughout the valley. In each stand, all species present were assigned a cover class: 1 = 0–10%, 2 = 10–25%, 3 = 25–50%, 4 = 50–75%, 5 = 75–90%, and 6 = 90–100%. Community types were identified through a combination of detrended correspondence analysis (Hill, 1979) and BMDP cluster analysis, using both species composition and physiognomy. Following classification, a vegetation map of Cascade Canyon (Patten, 1987) was developed using aerial photos, orthophotoquads, and field observations. Avalanche-prone areas were mapped from aerial photos and direct observation.

Previous research has demonstrated that avalanche frequency increases with elevation (Cushman, 1981; Johnson et al., 1985; Johnson, 1987), allowing elevation to be used as a measure of frequency in data analyses. To verify this relationship for Cascade Canyon, dendrochronological techniques (Potter, 1969; Shroder, 1976; Sauchyn et al., 1983; Johnson et al., 1985; Patten, 1987) were used to determine avalanche frequency at different elevations on both a north- and a south-facing avalanche track. Cross sections were taken from 10 to 15 trees that exhibited scarring from multiple avalanche events. Dating the scars through tree-ring analysis confirmed that avalanche frequency is positively correlated with elevation on the Cascade Canyon slopes (Patten, 1987). Because of this relationship, elevation was used as an indicator of relative avalanche frequency throughout this study. To control for effects produced by the elevational gradient

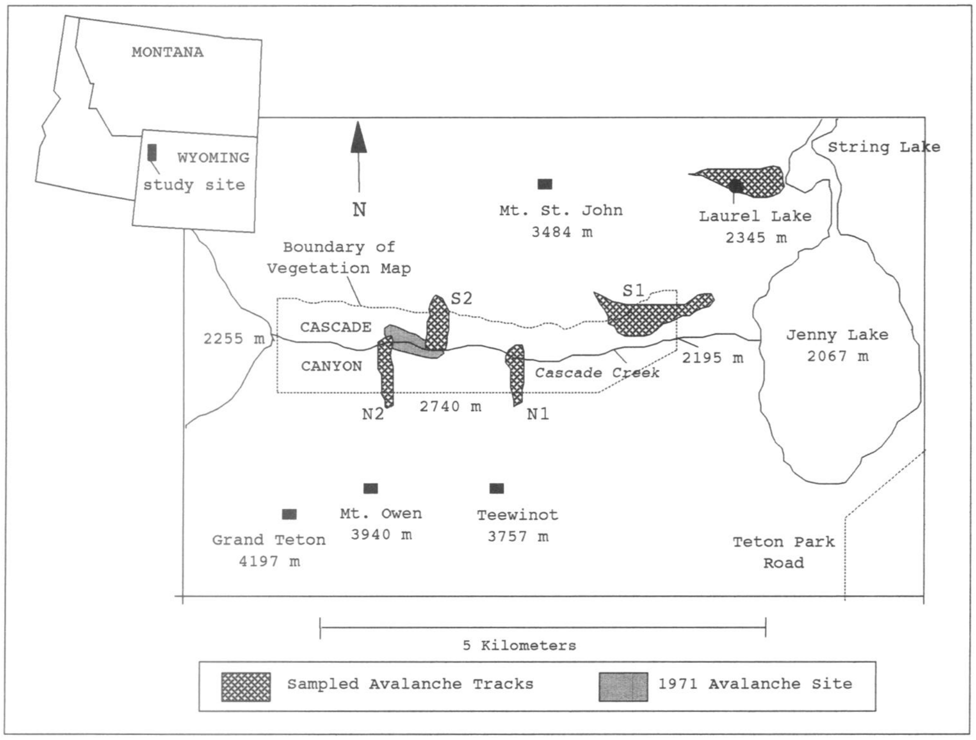

FIGURE 1. Location of the study area. Sampling was done over a 4.4 km² area in Cascade Canyon, Grand Teton Range, with intensive sampling on five avalanche tracks.

rather than changes in avalanche frequency, vegetation sampling was repeated in adjacent, undisturbed slopes.

To analyze community structure and composition in areas with frequent avalanches, sampling was done in the summer of 1986 on five tracks where avalanches probably occur every 1 to 5 yr (Fig. 1). Four of these tracks were within Cascade Canyon, two on the south-facing slope (S1 and S2) and two on the north-facing slope (N1 and N2). Tracks S2, N1, and N2 are typical of tracks with frequent avalanches that often run the full length of the track. Track S1, at the mouth of Cascade Canyon, has frequent avalanches throughout most of its length and also has an infrequently disturbed zone beyond the level valley floor on the far eastern edge of the canyon. Extensive tree damage occurred in this runout area in the winter of 1985–86.

A fifth track, the Laurel Lake track, was sampled north of Cascade Canyon. While avalanches frequently run from the overlying basin down to Laurel Lake at 2345 m, infrequent avalanches extend farther, down to 2130 m at the String Lake shore. Such an event occurred in the winter of 1985–86, causing considerable damage to forests below 2310 m.

Each of the five tracks was sampled in at least three areas, spaced from the highest accessible point (i.e. the cliff base of the south-facing slope and up to 2740 m on the north-facing slope) to the runout zone. Vegetation was sampled at each site using two 30 m transects placed 10 m apart. Shrub cover was recorded using the line intercept method; tree density was estimated by counting all trees within 1 m of the 30 m transects. The species and diameter at breast height (dbh) were recorded for each tree counted. This same sampling technique was used to sample undisturbed forests adjacent to tracks S1, S2, and N1, providing a control for altitudinal effects that might confound conclusions attributed to variation in avalanche frequency.

Areas of extensive tree damage on the lower portions of S1 and on the Laurel Lake track were used to identify the relationship of conifer size to damage. The species, dbh, and type of damage were recorded for each tree along five 30 × 2 m transects spaced 10 m apart. A total of 234 trees were recorded as being undamaged, leaning, broken, or uprooted.

Average conifer age, size, and growth rate were determined at each sample site by coring 10 to 15 randomly selected trees along each vegetation transect. Average annual growth rates were determined by using the ratio of dbh/age from each cored tree. The average dbh of each stand was based on all trees measured along the transects at each sample site.

The impact of infrequent, destructive avalanches was assessed by studying a large avalanche that occurred in 1971 within Cascade Canyon and two destructive avalanches that occurred in the winter of 1985–86 below S1 and at Laurel Lake (Fig. 1). The 1971 avalanche ran from the south-facing slope of Cascade Canyon across the valley floor and part way up the north-facing slope, destroying a 300-m² stand of forest. Two sites were sampled at this area, 71S on the south-facing edge of the valley floor and 71N on the north-facing edge (Fig. 1). Vegetation was sampled using the same methods as were used for sites on other avalanche tracks.

Results

AVALANCHE COMMUNITIES

The vegetation mosaic of the Cascade Canyon study area (Fig. 1) consists of 10 vegetation types (Table 1), as described in Patten (1987). The mosaic is fairly diverse and fragmented due to the numerous avalanches that occur within the Canyon. Fifty-two percent of the 4.4 km² study area is subject to avalanches with approximately equal areas of avalanche activity found on the north- and south-facing slopes.

The vegetation of the canyon is dominated by communities of either large conifer (average size greater than 15 cm dbh) or small conifer trees (average size less than 15 cm dbh), with 35 and 28% of the area covered by these two vegetation types, respectively (Table 2). Low shrublands and aspen shrublands

TABLE 1

Dominant tree and shrub species of the ten vegetation types identified in Cascade Canyon

Cover type	Tree species	Shrub species
Large-conifer (mean dbh > 15 cm)	*Picea engelmannii* *Abies lasiocarpa* *Pseudotsuga menziesii*	*Vaccinium membranaceum* *Menziesia ferruginea* *Sorbus scopulina*
Small-conifer (mean dbh < 15 cm)	*Abies lasiocarpa* *Picea engelmannii*	*Vaccinium membranaceum* *Sorbus scopulina* *Rubus parviflora*
Low shrubland (average height <0.5 m)		*Rubus idaeus* *Rubus parviflora* *Amelanchier alnifolia*
Aspen shrubland	*Populus tremuloides*	*Rubus idaeus* *Prunus virginiana* *Acer glabrum*
Aspen-conifer	*Populus tremuloides* *Abies lasiocarpa*	*Symphoricarpus oreophilus* *Prunus virginiana*
Matted subalpine fir	*Abies lasiocarpa*	
Tall shrubland (average height > 0.5 m)		*Lonicera involucrata* *Ribes inerme* *Menziesia ferruginea* *Salix* spp.
Riparian meadow (unidentified grasses and sedges)		
Aspen	*Populus tremuloides*	*Acer glabrum* *Rubus idaeus*
Cottonwood	*Populus trichocarpa*	

TABLE 2

The area and percent of the area covered by each vegetation type (plus talus and bedrock) in the study site and on avalanche tracks

Cover Type	Area (km²)	Percent of study area	Avalanche area (km²)	Percent of total avalanche area
Large-conifer	1.54	35	0.02	1
Small-conifer	1.23	28	1.22	53
Talus	0.62	14	0.37	16
Low shrubland	0.22	5	0.14	6
Aspen shrubland	0.22	5	0.18	8
Bedrock	0.18	4	0.02	1
Aspen-conifer	0.13	3	0.14	6
Matted subalpine fir	0.09	2	0.07	3
Tall shrubland	0.09	2	0.07	3
Riparian meadow	0.09	2	0.07	3
Aspen	0.04	1	0.005	<1
Cottonwood	0.005	<1	0.005	<1
Total Area (km²)	4.40		2.31	

TABLE 3

Distribution of communities in the Cascade Canyon study area, showing the percent of the community type found on opposing slopes and in avalanche tracks

Cover Type	South-facing	North-facing	Avalanche
Large-conifer	33	67	2
Small-conifer	33	67	99
Talus	67	33	62
Low shrubland	83	17	62
Aspen shrubland	91	9	95
Bedrock	17	84	18
Aspen-conifer	100	0	96
Matted subalpine fir	92	8	71
Tall shrubland	0	100	77
Riparian meadow	59	41	87
Aspen	98	2	23
Cottonwood	88	11	100

each account for 5% of the area, with the other six types (aspen-conifer, matted subalpine fir, tall shrubland, riparian meadow, aspen stands, and cottonwood stands) each covering only 3% or less of the area.

The abundance of communities on avalanche tracks is significantly different from the overall study area (Table 2). Small conifer stands cover 53% of the tracks, with 8% or less of the avalanche areas covered by any other single vegetation type.

Community distribution is dependent on both slope aspect and avalanche occurrence (Table 3). Over 90% of the aspen stands, aspen shrubland, aspen-conifer, and matted subalpine fir communities occur on the dry south-facing slope, along with 83% of the low shrubland. In contrast, two-thirds of the large conifer stands and all of the tall-shrubland communities are found on the mesic north-facing slope. Only a small percentage of the aspen stands or low shrublands are found on the north-facing slope.

Avalanche activity also influences where communities occur. Over 90% of the small conifer, aspen shrubland, and aspen-conifer stands are found in avalanche tracks. Of the other communities, only large conifer and aspen stands were found primarily outside of avalanche tracks.

WOODY COMPONENTS OF AVALANCHE COMMUNITIES

To determine how shrub species are affected by avalanche occurrence, variation in shrub cover was analyzed over the elevation gradient. Total shrub cover is positively correlated with elevation (thus avalanche frequency) on the north-facing Cascade Canyon tracks ($r^2 = 0.69$, $p < 0.025$) and the Laurel Lake track ($r^2 = 0.67$, $p < 0.10$), yet is not significantly correlated with elevation on the south-facing tracks (Fig. 2). No relationship was found between individual species distribution and avalanche frequency (Patten, 1987). Species composition of the shrubby component of avalanche communities appears to be site specific and, unlike total shrub cover, is not a function of avalanche frequency.

Conifer density increases with elevation on the north-facing slopes of Cascade Canyon ($r^2 = 0.5$, $p < 0.05$) and at Laurel Lake ($r^2 = 0.67$, $p < 0.10$) (Fig. 3). No relationship was found between conifer density and frequency on the south-facing slope.

Data comparing tree size with avalanche damage indicates that trees less than 10 cm in dbh are often undamaged by avalanches (Fig. 4). Small trees up to 15 cm dbh exhibit only minor branch damage and may be leaning downslope as a result of avalanche occurrence. Trees larger than 10 cm dbh are highly susceptible to breakage and uprooting when hit by an avalanche.

Conifer size, age, and growth rates are all related to avalanche frequency. Upper portions of avalanche tracks, where avalanche frequency is high, have significantly smaller ($p < 0.02$)

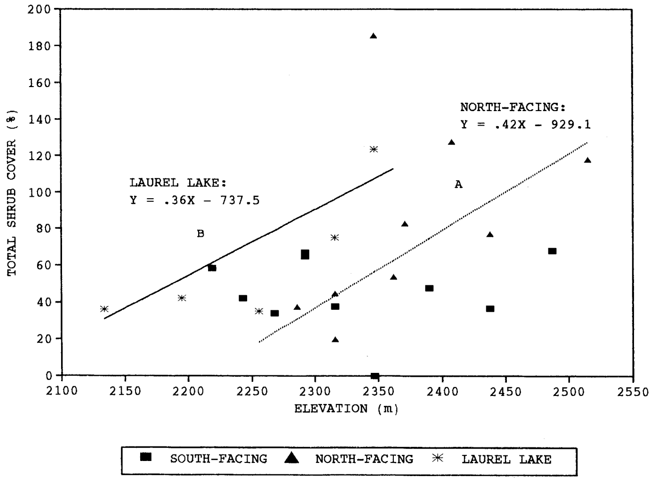

FIGURE 2. The relationship between elevation and shrub cover on avalanche tracks. Shrub cover is significantly related to elevation on the north-facing slope (line A) and at Laurel Lake (line B), but not on the south-facing slope.

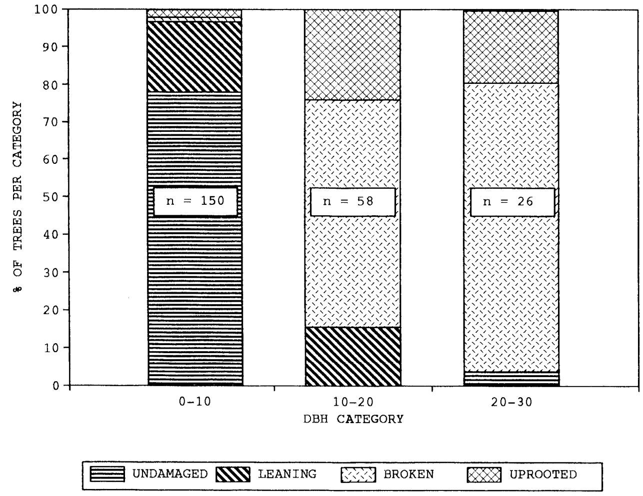

FIGURE 4. The relationship between tree size and avalanche damage. A majority of trees less than 10 cm dbh are left undamaged, while most trees larger than 10 cm dbh are either broken or uprooted.

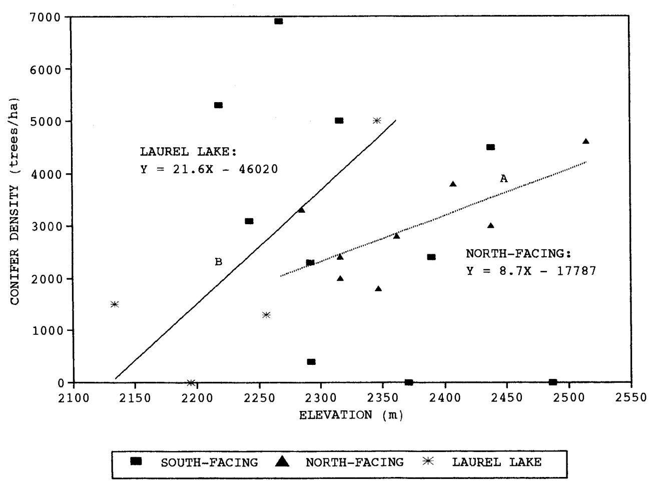

FIGURE 3. The relationship between elevation and conifer density on avalanche tracks. Conifer density is significantly related to elevation on the north-facing slope (line A) and at Laurel Lake (line B), but not on the south-facing slope.

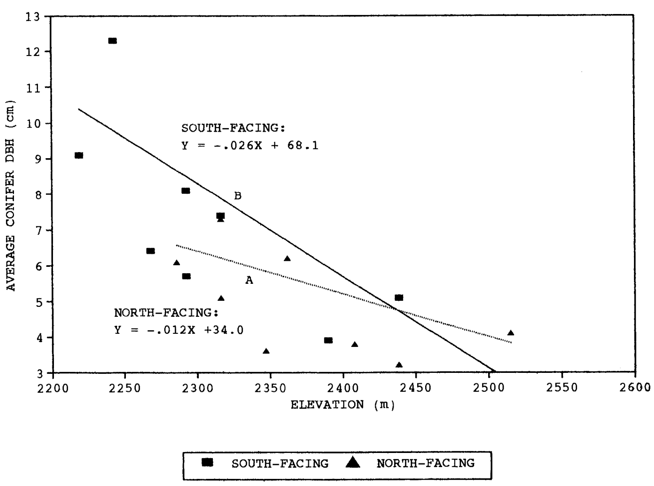

FIGURE 5. The relationship between elevation and conifer dbh on avalanche tracks. Dbh is significantly related to elevation on both north-facing (line A) and south-facing (line B) tracks.

average tree diameters than the lower runout zones. Average dbh decreases with increasing elevation on both the north-facing ($r^2 = 0.4$, $p < 0.05$) and south-facing tracks ($r^2 = 0.54$, $p < 0.025$) (Fig. 5). The size of trees on avalanche tracks is also significantly smaller ($p < 0.0025$) than on adjacent undisturbed forests. Tree size in undisturbed forests is not significantly different on upper and lower sections of the slope, indicating that avalanche frequency, and not the elevational gradient, is driving changes in dbh on avalanche tracks.

The average age of trees on avalanche sites was generally between 40 and 60 yr old. There is a significant increase in the average age of trees with elevation on the north-facing tracks ($r^2 = 0.43$, $p < 0.05$), but no relationship between age and elevation on south-facing tracks (Fig. 6).

Trees on upper portions of avalanche tracks tend to have slower growth rates than trees on lower track positions ($p < 0.05$). Conifer growth is also slower in tracks than in adjacent, undisturbed forests. Average growth rates are inversely related to elevation (Fig. 7) on both the north-facing ($r^2 = 0.40$, $p < 0.10$) and south-facing tracks ($r^2 = 0.65$, $p < 0.02$) of Cascade Canyon. Because of these slow growth rates, conifers in avalanche tracks can be up to 70 yr old despite their small size, resulting in smaller yet older trees in upper portions of the track. There is no significant difference in growth rates on upper and lower sites in adjacent, undisturbed forests. Again, this indicates that it is the frequency of avalanche occurrence that is driving variations in conifer growth rates on avalanche tracks rather than differences in elevation.

THE LANDSCAPE MOSAIC

Severe yet infrequent avalanches can cause extensive damage to stands of large trees and thus may cause changes in landscape patterns (Butler and Malanson, 1992). The potential impact of these destructive events on the patterns of the study area was assessed by studying the effects of avalanches that occurred in 1971 in Cascade Canyon and in 1985–86 below S1 and Laurel Lake.

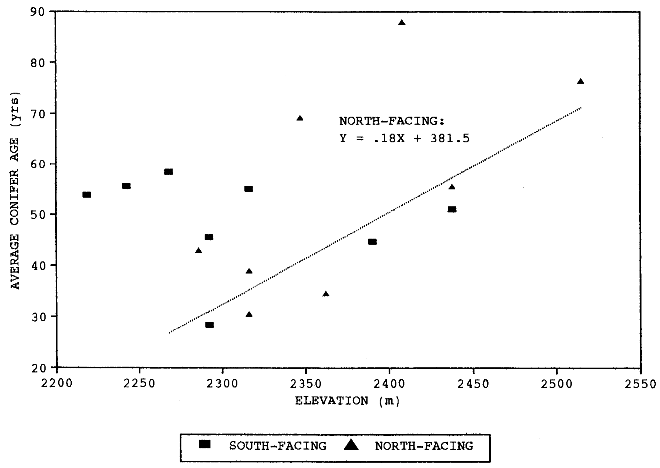

FIGURE 6. The relationship between elevation and conifer age on avalanche tracks. Age is significantly related to elevation on north-facing tracks, but not on south-facing tracks.

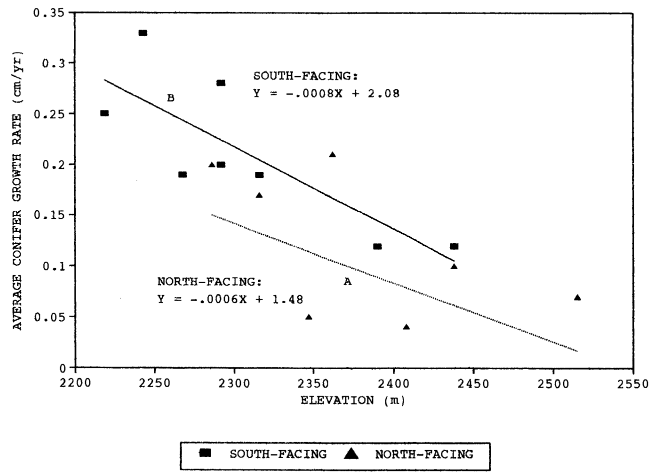

FIGURE 7. The relationship between elevation and average annual growth rate of conifers on avalanche tracks. Growth rate is significantly related to elevation on both north-facing (line A) and south-facing (line B) tracks.

The 1971 avalanche in Cascade Canyon destroyed approximately 300 m^2 of forest. Large down trees (greater than 20 cm dbh) and three surviving trees aged 165 to 188 yr old, indicate that a mature spruce-fir forest had previously existed in this area. Few new trees had become established in the 15 yr between the avalanche occurrence and the time of sampling.

The destructive potential of infrequent avalanches is further demonstrated at the S1 and Laurel Lake avalanches, which occurred the year prior to sampling. Virtually no trees were left standing at either location, although large trees were observed at these locations the previous summer. The average size of the trees destroyed at Laurel Lake was approximately 25 cm dbh with ages ranging from 31 to 73 yr old, averaging 42.6 ± 20.9 yr (n = 10). At the bottom of track S1, the downed trees also averaged around 25 cm dbh and ranged in age from 31 to 85 yr old, averaging 48.5 ± 20.9 (n = 10). The ages of the downed trees at Laurel Lake and track S1 suggest that it had been approximately 50 yr since an avalanche of this size had occurred.

Discussion

AVALANCHE COMMUNITIES

Many studies have noted that snow avalanches can have a significant effect on the composition and distribution of community types across a landscape (Khapayev, 1978; Butler, 1979, 1988; Cushman, 1981; Johnson, 1987; Malanson and Butler, 1984b; Erschbamer, 1989; Butler and Malanson, 1992). The vegetation patterns of Cascade Canyon illustrate how this disturbance type can affect the vegetation mosaic.

Avalanche occurrence in Cascade Canyon contributes to community diversity and increases the fragmentation of the vegetation mosaic. The influence of avalanches on community abundance and distribution is demonstrated by comparing community distribution within and outside of avalanche tracks. Stands of large conifers and aspen are found primarily outside of avalanche tracks, while a majority of the cover of all other communities occurs within the tracks (Table 3). Without avalanches, communities such as the small conifer stands may not exist and a greater percentage of the canyon would probably be covered by large conifer stands. Avalanches can therefore play a significant role in increasing the complexity and diversity of a region's vegetation mosaic.

Slope aspect can play an important role in determining the occurrence and frequency of avalanches (Butler, 1988), and also influences the effect of avalanches on vegetation. In Cascade Canyon, there is a significant difference in avalanche impacts and vegetation patterns on the north- and south-facing slopes. The dry, rocky environment of the south-facing slopes reduces total vegetation cover, diminishing the importance of avalanches in structuring community composition and distribution on this aspect. Consequently, there is a weaker relationship between vegetation patterns and avalanche frequency on the south-facing slope than on the north-facing slope (Figs. 2 and 3). This observation demonstrates the interaction of physical environmental factors and avalanche occurrence in controlling the vegetation patterns in Cascade Canyon.

WOODY COMPONENTS OF AVALANCHE COMMUNITIES

In addition to influencing the distribution of communities across the landscape, avalanches also affect the abundance and distribution of individual species within the community. The density of the woody components of avalanche communities is related to avalanche frequency. On the north-facing slope, the resilient nature of shrubs allows them to withstand repeated avalanche occurrence and increase in density as avalanche frequency increases. Shrub cover is not related to elevation or avalanche frequency on the south-facing slope, indicating that other environmental factors related to the dry, rocky conditions of this slope exert greater control over shrub distributions than avalanche frequency.

Shrub species found on Cascade Canyon avalanche tracks are similar to the species on tracks in other parts of the Rocky Mountains. Shrubs such as *Sorbus scopulina, Menziesia ferruginea, Salix* spp., and *Vaccinium membranaceum* are common on these avalanche tracks and have also been found on tracks in Montana (Stauffer, 1976; Butler, 1979) and Washington (Cushman, 1981). As has been noted elsewhere (Malanson and Butler, 1984b), shrub species composition in avalanche tracks is not explained by variation in avalanche frequency (Patten, 1987). The distribution of shrubs in these tracks is probably controlled by environmental factors other than disturbance, including moisture gradients, soil properties, and snowpack.

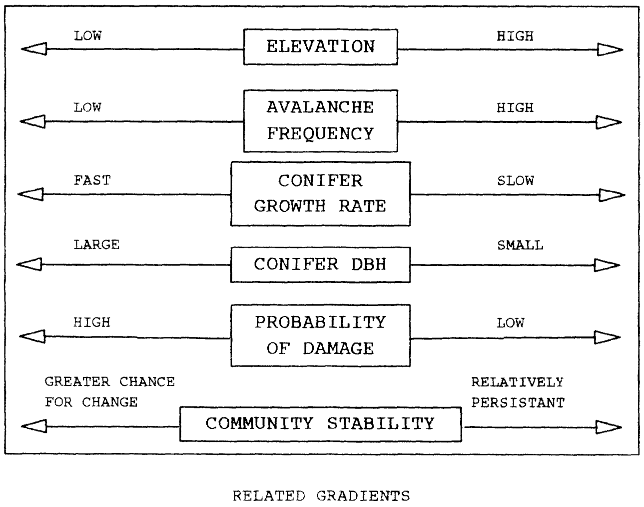

FIGURE 8. The stability of communities on avalanche tracks is related to several gradients that are a function of elevation. At higher elevations, avalanche frequency increases, reducing conifer growth rates and size. This decreases the probability of damage, reducing the chance of change within the community.

Although avalanche communities tend to be dominated by shrubby vegetation that is resilient to avalanche occurrence (Malanson and Butler, 1984a; Erschbamer, 1989; Butler and Malanson, 1992), small conifers can be an important component of the vegetation on the Cascade Canyon tracks. In this area, conifer density increases with avalanche frequency on north-facing slopes, yet shows no relationship to avalanche frequency on south-facing slopes. These results differ from other studies which found a decrease in conifer density as avalanche frequency increases (Butler, 1979; Johnson, 1987). Many of the Cascade Canyon avalanches run the length of the slope, reaching the valley floor. This relatively high avalanche frequency throughout the length of these tracks may inhibit any increase in density near the runout zone of the tracks.

Despite the fact that avalanches do not adversely affect conifer density in Cascade Canyon, they do have an impact on other aspects of conifer survival and growth. Conifer survival in avalanche tracks is partly a function of tree diameter, as the probability for damage or mortality is related to size (Potter, 1969; Mears, 1975; Butler and Malanson, 1985; Johnson, 1987). Because of the relationship between size and breakage, trees can continue to grow with little probability of being destroyed until they reach a certain size, approximately 10 cm dbh. Beyond this point, avalanche damage may be severe, killing the tree.

The growth rate of trees in avalanche tracks is inversely related to avalanche frequency, with slower growth rates at higher frequencies. These growth rates are significantly less than in adjacent, undisturbed forests, as was also found in a study completed by Eversman (1968) in Montana. The direct cause of the slower growth rates appears to be a function of avalanches rather than other factors related to elevation, as adjacent undisturbed forests do not exhibit a decrease in growth rates up-slope. Growth rates are significant in determining the length of time trees can survive in areas frequently subjected to avalanche occurrence. Because the trees in active avalanche tracks are slow growing, they can live a relatively long time before reaching a size where they are likely to be destroyed. For example, a tree growing at 0.15 cm yr^{-1} dbh that was 10 yr old at breast height will be 77 yr old before it reaches 10 cm dbh. The persistence of conifers in avalanche zones is thus a function of their slow growth rates and small size, maintaining the community despite frequent avalanche occurrence.

THE LANDSCAPE MOSAIC

The primary effect avalanches have on the Cascade Canyon landscape is to increase the diversity of communities and the fragmentation of the vegetation patterns. Although disturbance may result in continual changes in vegetation patterns by creating communities in various stages of succession (Odum, 1969; Pickett and Thompson, 1978; Shugart and West, 1981; Pickett and White, 1985), the patterns of the vegetation mosaic may be fairly stable in mountain areas where the major disturbance is frequent avalanches. Avalanches tend to occur in the same location at fairly regular intervals, often with little impact on underlying soils (Butler and Malanson, 1990). Vegetation in avalanche tracks is apparently resistant to this continual disturbance, creating disclimax communities that are persistent, with few changes in structure or composition over time (Cushman, 1981; Butler, 1985, 1988; Johnson, 1987; Patten, 1987; Erschbamer, 1989).

The persistence of avalanche communities is in part a function of how frequent avalanches affect conifers within an avalanche track. Frequent avalanches result in community persistence through constant removal of trees larger than 10 cm dbh, reducing the average size of trees in the stand. The continuous thinning of larger trees that occurs with a high avalanche frequency removes only one or two trees at a time rather than causing extensive damage to the stand, thus the changes in community structure due to avalanche occurrence are minimal (Johnson et al., 1985; Johnson, 1987).

A second way that frequent avalanches contribute to persistence in avalanche community structure and composition is by reducing growth rates. This effect may be a result of repeated stress from disturbance, as scarring, bark damage, or needle damage may reduce overall productivity. As avalanche frequency increases, average growth rates decrease, thus trees remain at sizes less than 10 cm dbh for longer periods of time. Because conifer damage is size-related, stands of small trees are less likely to be damaged or show changes in stand structure, thus less change occurs in communities where avalanche frequency is high.

These results demonstrate that the stability of avalanche communities is a function of several gradients related to elevation and avalanche frequency (Fig. 8). Avalanche frequency increases with elevation, contributing to the slow growth rates of conifers in the higher elevations of the track. This results in smaller trees that have a lower probability of damage on the upper slopes, stabilizing these communities by reducing the chances that avalanches will create a change in the community structure. Thus, community stability is greatest at higher elevations where avalanches are more frequent.

Although communities occurring in areas of frequent avalanches appear relatively stable, vegetation in areas where less frequent avalanches occur can be severely damaged by avalanche occurrence (Butler and Malanson, 1992). Extreme damage of this type was observed in the 1971 and 1986 avalanches in Cascade Canyon. Yet these destructive events may not significantly influence overall dynamics of this mosaic, as field observations suggest that they have limited occurrence in Cascade Canyon. The three areas described here were the only locations in the study area where avalanches had a major impact on vegetation. These disturbed sites constitute less than 1% of the mapped region. Highly destructive avalanches therefore probably have only a minor influence on the vegetation patterns of Cascade Canyon.

Although there is no evidence that avalanches drive large scale changes in landscape patterns of Cascade Canyon, they do have a significant effect on the area's vegetation mosaic. Avalanches increase both community diversity and the fragmentation of the Canyon's landscape, potentially affecting species diversity, population dynamics, and vertebrate movement (Levin, 1976; Wiens, 1976; Lord and Norton, 1990; Maurer, 1990; Saunders et al., 1991; Hobbs and Huenneke, 1992). Avalanches are therefore an integral part of this mountain system, playing an important role in the system's patterns and processes.

Acknowledgments

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