

**SPATIAL CHANGES IN  
ALPINE TREELINE VEGETATION PATTERNS  
ALONG HIKING TRAILS IN  
GLACIER NATIONAL PARK, MONTANA**

by

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# Spatial Changes in Alpine Treeline Vegetation Patterns along Hiking Trails in Glacier National Park, Montana

**ABSTRACT:** Sequential aerial photography was used to identify effects of hiking trails on the spatial distribution of subalpine fir (*Abies lasiocarpa*) habitat at alpine treeline. Vegetation change over a 46 year period was compared along trails relative to areas without trails, at five study sites in the McDonald Creek drainage of Glacier National Park. Paired trail and nontrail test areas (22-35 ha each) were selected to be as identical as possible in all respects except for the presence of a hiking trail. Measured characteristics (number of patches, patch area, and edge density) were based on a morphological classification of subalpine fir vegetation (krummholz and patch forest) from black-and-white aerial photography. Results suggest that the number of small, discrete krummholz stands has increased at sites where trails are present relative to sites without trails. Terrestrial photography expanded the time scale considered, and supports the conclusion that fragmentation of krummholz is more evident along trails compared to areas without trails. However, other measures of change in krummholz and patch forest do not suggest a noticeable effect of trails over the area (278-ha total) studied.

## INTRODUCTION

Trails are more than paths created from the weight of many feet. Human activities along trails which can change vegetation patterns include trampling, construction, pollution (oil, herbicides, etc.), firewood and wildflower gathering, picnic sites, social trails, and introduction of non-native species (cf. Price, 1985). Other changes associated with human activity and altered vegetation patterns include wildlife attracted to or repelled from humans, nutrient loading from animal and human waste, and animal geomorphic activity (such as wallows, dens, and other excavations; cf. Butler, 1995), and altered snow accumulation (Daly, 1984) and runoff. Yet trails, like those found in Glacier National Park, Montana, are believed to have little spatial effect

from trampling beyond ~5 m of the trail edge (Weaver et al., 1979). Trails however, may function as a boundary or barrier between two habitat types, reinforced by positive feedback between changes in vegetation and human behavior (Wilson and King, 1995).

Trees are the dominant structural component of alpine treeline ecosystems and their response to long-term trends reflects underlying changes in this ecosystem. Repeated aerial photography provides a means for discerning spatial changes along trails at alpine treeline. Identifying change in vegetation helps land managers recognize natural and human-driven processes and aids in determining a desired resource condition (cf. Vale, 1987). This study looks specifically at changes in the spatial distribution of 'trees' at alpine treeline due to the presence of trails.

### **Objective**

*Do trails have tangible spatial effects on krummholz and patch forest distribution, at smaller scales (larger areas), than suggested by traditional trampling studies?* Repeated black-and-white aerial photography is used as a simple and inexpensive means to identify such change and direct further research.

Human activities associated with trail use (trampling, toxic leaching, removal of woody vegetation, soil compaction, etc.) are hypothesized to reduce krummholz ("patches of wind-crippled, stunted, dwarfed, or matted tree forms, alternating with herbaceous 'openings'") and patch forest ("a mosaic of openings and patches of symmetrical trees"; Weisberg and Baker, 1995a:117) expansion into meadow and shrub habitats by increasing mortality and reducing growth rates. Relative to areas without trails, patch forest and krummholz are hypothesized to increase in area at a

slower rate along trails, increase in patch edge-density more rapidly along trails, and increase in number of distinct habitat patches along trails.

### **Effects of Human Activity along Trails**

Human activity alters treeline vegetation patterns. The effects of this activity on vegetation depend upon amount of use, type of human activity involved, physical environment, and plant species (Cole, 1978; Weaver et al., 1979). For example, tree seedlings are more susceptible to trampling and compaction than meadow or grass; and forest habitats recover more slowly from trampling than alpine meadow or grassland (Weaver et al., 1979). Also, areas with high soil-moisture are the most easily damaged by trampling, with tall herb and turf ecosystems progressively less affected (Willard and Marr, 1970). Dispersed damage from trail activity (e.g. trampled or injured trees, compacted soils, or species specific mortality) may not be obvious, but is critical to tree establishment and growth. Sites with shrubs and moist soils are associated with the greatest rates of tree establishment and growth (Hessl et al., 1996; Rochefort and Peterson, 1996), and are the most adversely affected by trampling (Willard and Marr, 1970; Cole, 1978). Trampling initiates accelerated natural erosion in heather (*Phyllodoce* spp.) communities (Edwards, 1979), and frequently results in bare, compacted, or eroded soils which preclude tree establishment and retard growth. De Gouvenain (1996) found that soil compaction from trampling results in long-term effects on successional development and localized effects from recreational activity on growth rates within subalpine tree stands.

Vegetation damage by humans is often qualitatively different from damage due to natural disturbances. For example, de Gouvenain (1996) was able to differentiate

among soils where mechanical disturbance (from heavy or motorized equipment) had occurred by measuring soil water content and temperature gradients. Successional processes can be altered through the introduction of non-native plant species, with trails serving as corridors for introduction to larger regions. Also, discarded food and human and animal waste provide nutrients (such as nitrogen) which favor growth of plants located near where the waste is deposited (Dale and Weaver, 1974).

Human behavior serves to retard an already slow rate of change in the krummholz zone and in patch forests. People often remove dead wood, which protects living krummholz from the effects of wind, snow, and cold (Ives and Hansen-Bristow, 1983). Dude-ranch tours, hikers, and horse-packers in Glacier National Park frequently gathered firewood in the subalpine region earlier this century. Social trails (user-created trails) located around heavily used sites increase the area affected. Patch edges are often preferred travel routes (Price, 1986), although well-defined and maintained trails concentrate people and reduce this tendency. Rock collection, flower picking, littering, and crushing of plants by vehicles are other activities which affect alpine and subalpine vegetation (Willard and Marr, 1970).

Management practices have influenced the effects of trails on vegetation in Glacier National Park. The removal of brush along the edge of trails or rerouting of trails widens the spatial effects of trails by exposing different vegetation. Early season access to otherwise remote trailheads often leads to trail tread established in the snow on top of existing vegetation which does not match the intended route. During the 1930s, "the dust menace" was eliminated, so visitors could "inhale the gloriously invigorating mountain air," by applying light, penetrating oil on heavily used trails every

three to four years (Reed, 1932). Before spreading the oil, trails were graded, with ditches cleaned and widened. Further disturbance resulted from the method of application, a Cletrac (a small, narrow bulldozer) or horses drawing up to two 150-gallon tanks on a tender. A hand oiler was used along less accessible stretches of trail (Figure 1). Although the exact chemical constituency of the oil used is uncertain, the effects of petroleum on soils have physical and biological consequences that can increase tree mortality (Collins et al., 1994). In 1975, die-back of subalpine fir (*Abies lasiocarpa*) was documented more than 7.6 m from the Logan Pass trail because pentachlorophenol (PCP), a soil disinfectant, was leaching from impregnated wood



**Figure 1.** Hand oiling of the trail to Sperry Chalet, ca. 1932. Photo courtesy Glacier NP archives.

used to construct a boardwalk (Beaver, 1975). More recent efforts to minimize effects of large amounts of human use include the application of asphalt, although its effects (petroleum residues and heavy metals can leach from asphalt; cf. Phelan and Rhodes, 1966; Munch, 1992) on soil and vegetation are greatly reduced when compared to direct application of oil.

### **Spatial and Temporal Scales of Vegetation Change**

Appropriate spatial and temporal scales need to be identified when evaluating changes in the distribution of alpine timberline vegetation (Clark, 1985). Over the past



100 years, these changes are driven primarily by climate gradients and physical disturbances (Stevens and Fox, 1991; Rochefort et al., 1994; Cairns and Malanson, 1997). Time scales necessary to evaluate climatic forcing of vegetation require  $10^0$  -  $10^2$  years, and spatial scales range from  $10^{-4}$  -  $10^8$  km<sup>2</sup> (Peterson et al., 1997). Changes in the scale of physical disturbances (fire, wind, avalanches, etc.) are typically pervasive throughout a local habitat type. However, the distribution and interaction of different disturbance types change over time and space (Veblen et al., 1994). In Glacier National Park, alpine treeline has not exhibited a discernible pattern of advance due to climate along spatial or temporal scales since the Little Ice Age (Butler et al., 1994; Allen and Walsh, 1996).

### **Vegetation Change through Growth and Establishment**

Trees are readily distinguished from other vegetation in black-and-white photography, and thus photography is commonly used to identify changes in their distribution and infer other changes in the ecosystem (c.f. Vale, 1987). Tree growth-ring width is often used to identify past climatic conditions (c.f. Lawson and Stockton, 1981). Tree growth-ring width is also correlated with known climatic conditions to identify favorable climates for growth and establishment (c.f. Rochefort and Peterson, 1996). Although climate is often described as the primary forcing mechanism for vegetation change at treeline, other interpretations can be found. In the Swiss Central Alps, the montane pine (*Pinus* spp.) ecocline "seems to be stabilized by species interactions and may not be directly responsive to moderate climatic change" (Hättenschwiler and Körner, 1995:357).

One way in which vegetation patterns can change is from growth of individual trees. This growth can occur through shoot leaders (vertically), laterally, or radially (thickness). In Rocky Mountain National Park, krummholz leader growth in subalpine fir and Engelmann spruce (*Picea engelmannii*) is more rapid in open sites or sites with moist soils, and is greater than shoot mortality (Weisberg and Baker, 1995a). This leader growth may eventually shift the krummholz to patch forest. Radial growth in patch forest is more rapid than radial growth in krummholz, and is greater where associated shrub species (*Vaccinium* spp., greater yet with *Salix* spp.) are present (Hessl et al., 1996:206). Growth rates among treeline species are most similar for subalpine fir and Engelmann spruce, although rates differ by slope and aspect (Peterson and Peterson, 1994). In Glacier National Park, lateral expansion of "krummholz islands" through vegetative reproduction is described as rapid (Habeck, 1969:67).

Tree establishment is also capable of altering vegetation patterns. Modeling studies in Glacier National Park identify two major influences precluding establishment: slope instabilities and "a process other than physiological stress, probably reproduction" (Cairns, 1998:37). In response to more favorable climates, establishment is generally widespread within local landscape units (Rochefort and Peterson, 1996). In Mt. Rainier National Park where widespread establishment of seedlings is occurring, the highest density and survival rates for tree establishment are in dwarf shrub (especially *Phyllodoce* spp.) habitats (Rochefort and Peterson, 1996). In Rocky Mountain National Park, seedling establishment in krummholz openings is uncommon except in willow (*Salix* spp.) wetlands. Yet rapid establishment in patch forest openings (especially

mesic, *Vaccinium* spp. dominated sites) suggests the possibility of a shift to closed forest types (Weisberg and Baker, 1995b). Invasion of alpine tundra by trees during the past 100 years was suggested by Habeck (1969), based on observations at Logan Pass in Glacier National Park. Butler et al. (1994) however, identified a general stability in treeline, and suggested that establishment is evident at sites with favorable climate and little disturbance. Much of the distribution of existing treeline vegetation observed by Butler et al. (1994) can also be explained by topographic factors (solar radiation potential, snow accumulation potential, and soil saturation potential) (Brown, 1994).

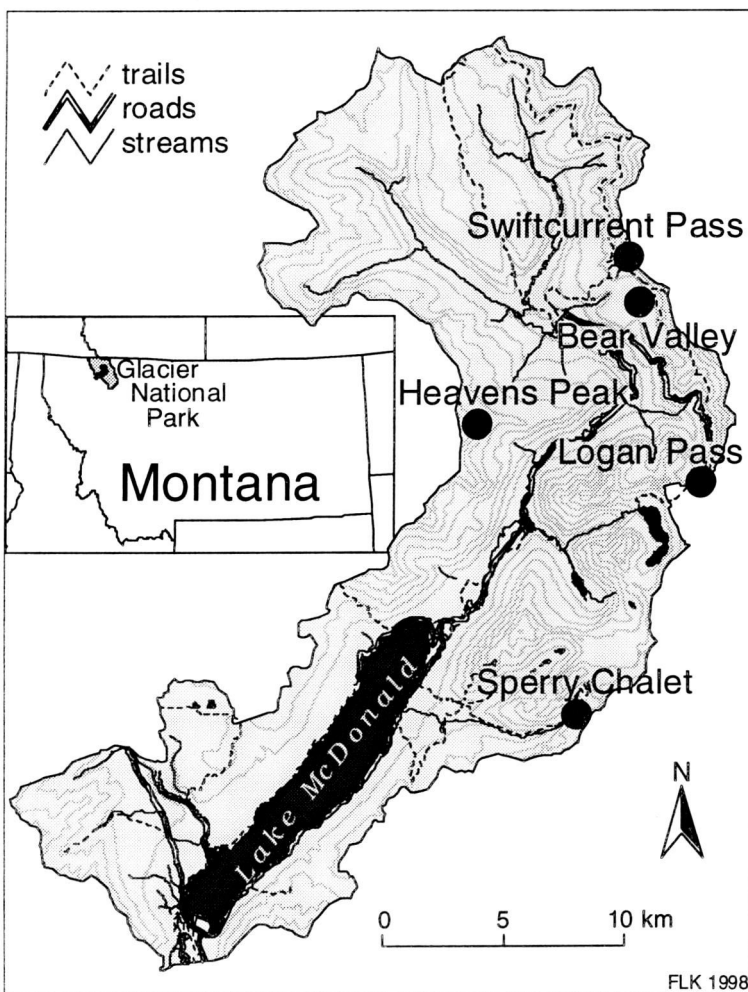
### **Other Influences**

Treeline responses to climate change "depend on the inclusion of indirect responses, especially to changes in disturbances" in addition to climatic gradients (Allen and Walsh, 1996:1262). Noticeable changes in the magnitude of avalanches at treeline, which could alter basin-wide vegetation patterns, have not been found to be influential at sites in Glacier National Park over the past ~70 years (Butler et al., 1994). However, the distribution of other disturbance sources, like fire, have changed. Influences that can complicate spatial changes at treeline cover multiple scales—from basin-wide disturbances like fire, to pack-stock or wildlife grazing, to microclimates and soil patterns. Grizzly bears (*Ursus arctos*), for example, move large volumes of soil and maintain extensive diggings for food, which affects soil erosion rates (Butler, 1992). The role of grizzly bears in maintaining meadow habitats and increasing nitrogen availability to plants is also being investigated (Tardiff and Stanford, submitted).

## METHODS

### Study Area

Glacier National Park (4079 km<sup>2</sup>) straddles the continental divide in the Rocky Mountains of northwest Montana, bordering the Canadian provinces of Alberta and British Columbia. The five alpine treeline sites in this study were between 1950-2200 m elevation, near the upper edges of the McDonald Creek drainage (448.7 km<sup>2</sup>) (Figure 2). The study sites were: Logan Pass, along the continental divide and Going-to-the-Sun Road, with a visitor center and trail to Hidden Lake; Sperry Chalet, adjacent to the



**Figure 2.** Alpine treeline study sites, McDonald Creek Drainage, Glacier National Park, Montana.

Chalet with trails leading to it from the valley below and passes above; Swiftcurrent Pass, along the continental divide above Granite Park Chalet, bisected by a trail through the pass; Bear Valley, adjacent to the Granite Park area with a trail traversing through the site; and a control site, Heaven's Peak, ribbon forest (parallel bands of patch forest, separated by moist meadows; Arno and Hammerly, 1984) in a cirque basin without known trails.

The highly glaciated topography ranges from about 960 m elevation at valley bottom to 2800 m at mountain summits. Significant glacial advances and moraine formation occurred most recently in the mid-19<sup>th</sup> century, during the most severe climatic cooling since the end of the Wisconsin glaciation (Carrara, 1989). Study-site soils are generally shallow and rocky, originating from a combination of bedrock and volcanic (Mazama) ash (Land and Water Consulting, 1994; Land and Water Consulting, 1995).

McDonald Drainage is dominated by warm, moist Pacific air masses. The wettest months of November, December, and January receive mostly snow, with occasional heavy rains in spring accompanying snowmelt. July and August are the driest, with total annual precipitation often in excess of 200 cm (Finklin, 1986). Estimated mean temperatures at 1830-m elevation are -8°C in January and 14°C in July, with an adiabatic lapse rate of 7.8°C/1000 m (Finklin, 1986:10). West Glacier, Montana, long-term trends (1920-1990) in average annual precipitation, snowfall, and average daily January and July temperatures are relatively stable—with a slight peak in precipitation and snowfall in the 1950s and 1960s. Long-term trends (1969-1990) at Flattop Mountain SNOTEL station (1920-m elevation) are similarly stable.

Timberline vegetation patterns in Glacier National Park, as in the entire northern Rockies, are erratic (Griggs, 1938), although believed to be advancing upwards (Habeck, 1969). Alpine timberline tree species are dominated by subalpine fir (*Abies lasiocarpa*), with mixtures of Engelmann spruce (*Picea engelmannii*), Douglas-fir (*Pseudotsuga menziesii*), mountain hemlock (*Tsuga mertensiana*), limber pine (*Pinus flexilis*), and whitebark pine (*P. albicus*) (Pfister et al., 1977). The upper subalpine

forests consist of uneven-aged stands, with sporadic stand-replacement fires at lower elevations and patchy, highly-localized fires at upper elevations (Barrett, 1988; Barrett, 1997). Swiftcurrent Pass and Bear Valley are the only study sites that have burned in the past 100 years, with a small portion of the Bear Valley study site burned in the 1967 Glacier Wall fire. Fire exclusion combined with increased mortality from disease (blister rust) and mountain pine beetle infestation have resulted in an increase in spruce-fir cover type while limber and whitebark pine have declined (Barrett, 1997).

People began to systematically exploit the alpine zone in the Northern Rocky Mountains after 4000 BC, and left a lasting imprint from trails, encampments, hunting, and gathering (Husted, 1974). Many peaks and open, high points in Glacier National Park are religious sites. The Swiftcurrent Pass area had a prominent American Indian trail and a prospector's cabin located near the present Granite Park Chalet. Logan Pass was also used by native people and trappers. Although such consistent use at the other study sites has not been as explicitly documented, the treeline region in general provided passage, supplies, and shelter for visitors. While American Indian use may have declined since the area became a National Park, other uses have increased. The region was declared a 'forest park' in 1895, and designated Glacier National Park in 1910. Prior to World War II, it was primarily a horse-park, where most visitors toured the backcountry on horseback. In 1933, with the opening of the Going-to-the-Sun Road, the interior became more accessible, and increasing numbers of hikers entered the backcountry. With the exception of forest fires, identifiable human effects on vegetation have been predominantly related to roads, trails, chalets, and campsites.

The five study sites considered have different use-histories. Visitor use at all sites has shifted from American Indian foot traffic to intensive horse or recreational hiker traffic. At Sperry Chalet, Swiftcurrent Pass, and Bear Valley, horse use continues to this day. Besides horses, no documented use of other domestic stock or grazing has occurred at the study sites (Buchholtz, 1976). Logan Pass has experienced the most significant increase in the number of hikers. Soil compaction, increased erosion, reduced species cover, and altered species composition are most evident at Logan Pass, but can be found along trails at all of the study sites.

### **Site Selection**

Study sites contained either krummholz or patch forest and, with the exception of Heavens Peak (control site), were bisected by a trail. Criteria for reducing variability in each site were a relatively large area (~2 km<sup>2</sup>) with similar slope, aspect, and habitat type distribution between the paired sites. Sites with repeated physical disturbances, such as avalanche paths, were avoided where possible. Tree growth and establishment are controlled primarily by topography and existing vegetation type (Rochefort and Peterson, 1996). Therefore, climate, geology, and soils were assumed to equally affect similar vegetation types at a single study site. Variability in tree growth and establishment from these sources considered to be minimal when making comparisons within study sites.

### **Image Classification**

Black-and-white aerial photographs from 1945 (August) and 1991 (August) were obtained for each site. Black-and-white photography is not an ideal medium for interpretation and mapping of alpine treeline vegetation types (cf. Baker et al., 1995).

However, consistency in image interpretation (photographs from 1945 were the earliest complete set and available only in panchromatic black-and-white) outweighed the benefits of improved classification gained from comparing different image types between the two dates. The 1991 images were in print (1:40,000 scale) and digital format (USGS Digital Orthophoto Quadrangle [DOQ], 1:24,000 scale, 1-m ground sample distance). The 1945 prints (1:15,000 scale) were scanned to approximate 1991 DOQ resolution. Distortion in the 1945 images was corrected to the 1991 DOQ's in a Geographic Information System (GIS) using a 3<sup>rd</sup> order polynomial transformation and a minimum of 17 ground control points per image. Although an error of  $\leq 0.5$ -pixel root mean square (rms) is recommended for digital change detection (Jensen, 1996), rectification error for the 1945 images was less than 5 pixels (5-m) rms (typically  $\sim 2.5$ -pixels rms). Therefore, descriptive landscape metrics similar to those identified by McGarigal and Marks (1995) were calculated and compared, rather than performing traditional digital change detection.

For both 1945 and 1991 images, vegetation classifications were assigned and delineated using brightness (reflectance) values. The initial assignments were refined using a supervised classification based on texture and shape, stratified by spatial clustering and density. Confirmation of all classification assignments through manual image interpretation was possible, given the relatively small area studied, and an error matrix was not constructed. Vegetation (habitat) types assigned were: open forest (symmetrical trees with a well-distributed, non-patterned canopy), patch forest, krummholz, dwarf shrub/wet meadow (moist sites with rushes, heather, and other woody species), dry meadow (grasses, forbs, and cushion plants which quickly dry out



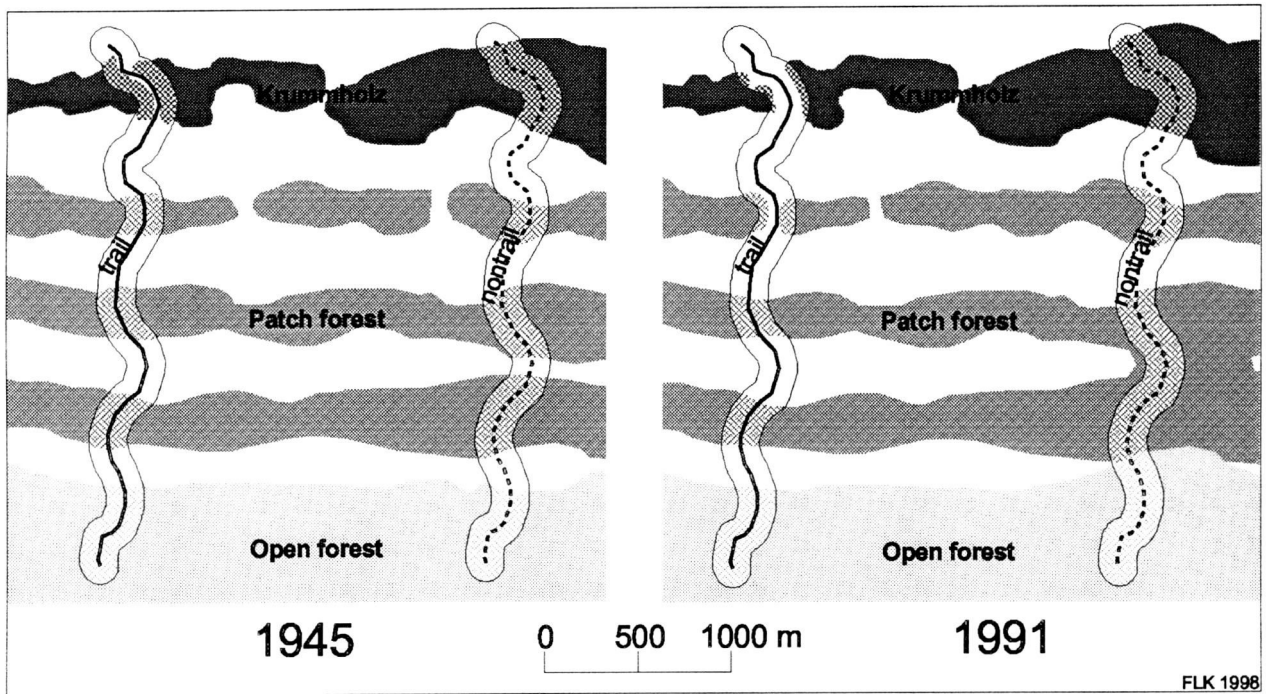
after snowmelt), rock, snow, and water. Vegetation classes assigned were derived from the alpine classification for Glacier National Park developed by Habeck (1970), with reference to previous and later classifications (National Park Service, 1936; Achuff et al., 1997). As black-and-white photography limited differentiation between certain vegetation types, Habeck's (1970) classification was simplified based on identifiable characteristics in the photography and the discussed significance to tree growth and establishment. Classification assignments were field-validated in 1995-1997 (Kendall, 1998: unpublished data).

Identification of vegetation type (especially patch forest and krummholz) was possible primarily through image shape and texture, which required larger areas for context. Therefore, regions of assigned vegetation less than 25-m<sup>2</sup> were reassigned to the surrounding classification. Also, most field data collected were for areas of ~400 m<sup>2</sup>, making classification of small areas less accurate. Individual trees, the density of trees, or smaller habitat patches are thus not considered in this study. Rather, the expansion of habitat patches, through vegetative growth or establishment immediately adjacent to similar vegetation, is evaluated.

### **Comparison of Vegetation**

Vegetation surrounding two parallel segments defined in each image (1945 and 1991) was compared in ArcView<sup>®</sup> GIS. Trails were digitized from the 1991 images. A segment of trail (~1-2 km in length) was copied from the 1991 image and pasted to the same location in the 1945 image. The same linear shape was then pasted up to 2 km from the actual trail in both images (1945 and 1991), and designated as 'nontrail'

segments. Nontrail segments were located parallel to the actual trail and at the same place in the alpine treeline gradient, as shown in Figure 3.



**Figure 3.** Hypothetical example of change in vegetation patterns—trail segments (solid line) compared to nontrail segments (dashed line) within 100 m.

The effects of trails at smaller scales (larger areas), especially effects extending more than ~5-m distance from the edge of a trail, were of interest. Hartley (1979) found fewer species beyond this distance which respond to a trampling gradient. With trails at the study sites 1-2 m wide, a typical 2-dimensional expression of the effect of trails was therefore considered to be ~6-m perpendicular in either direction from the center of a trail. Measurements were taken on both images (1945 and 1991) for the area within a 100-m buffer distance around the paired trail and nontrail segments, more than ten times the distance of commonly identified trampling effects. This distance easily encompassed any changes in trail location which had occurred prior to and during the study period. Thus the area of each nontrail or trail site was between 22-35 ha

(identical for each pair within the five locations) and the total area studied was 278 ha (combined trail and nontrail for all five sites).

For every image, trail segment measurements made were: length of segment through each habitat type and number of bisected patches. Measured patch (polygon) characteristics were: total number of patches, patch area, and edge density. Measurements at each site were sorted by habitat type. Since relative change between trail and nontrail sites was of interest, area and length measurements were expressed as percentage change from total (1945 to 1991) by tree habitat type. Counts of total number of patches, number of bisected patches, and edge density were expressed as change from 1945 to 1991 by tree habitat type.

In this study, patch characteristics are indicative of potential widespread influences of trails. Change in percent area, which indicates landscape composition (McGarigal and Marks, 1995), is interpreted as reflecting the expansion or contraction of krummholz or patch forest. Number of patches is a measure of landscape heterogeneity reflecting fragmentation of existing patches and simultaneously the establishment and expansion of small clusters of vegetation. Edge density (edge/area, for the total area of a single habitat type) is indicative of landscape heterogeneity and reflects patches becoming smaller due to fragmentation (increased edge density) or patch edges being smoothed around the perimeter while leaving a central core intact (decreased edge density).

Sampling of landscape elements using linear traverses is also a common method in landscape ecology (Kienast, 1993). In this study, segment features had no width, and the associated measures are based on the habitat types intersected. The

removal of clusters less than 25-m<sup>2</sup> results in the percentage segment through each habitat being a measure of how distinct a trail is in a photo. A change in the number of bisected patches responds to either the spreading apart of habitat types or an increase in the width of a trail. Careful interpretation of results is required to ensure that image registration error was equal across both trail and nontrail sites.

Analysis of variance (ANOVA) was used to evaluate if overall differences (measures of krummholz and patch forest habitats combined) were attributable to the effect of trails, or if observed variability was attributable only to site characteristics. Log transformation of the ANOVA data was necessary to equalize variance between groups. When evaluating differences by habitat (krummholz and patch forest separately) the number of observations was limited, and the Mann-Whitney Rank-Sum test (rank transformation) was used. Differences attributable to area of habitat types in 1945 and average patch size in 1945 were also evaluated for patterns consistent with observed responses. As suggested previously, such comparisons are relevant since krummholz and patch forest establishment is determined in part by available surrounding habitat types and soils (with vegetation often a good indicator of soil type in alpine environments). Specific questions of interest about the difference in change from 1945 to 1991 between trail and nontrail regions, were:

- Is the areal expansion of krummholz and patch forest precluded in areas with trails?
- Does edge density of krummholz and patch forest increase along trails?
- Do the number of patches of trees increase along trails?
- Which tree habitat types are most susceptible to the effects of trails?
- Which measurement characteristics respond most to the presence of trails?

## ANALYSIS

### Data Summary

Changes in both patch and segment measures do not suggest a noticeable pattern of an effect from trails, as seen in Table 1. There is no consistent magnitude or direction (+ or - values) of change for any of the five measures at either trail or nontrail sites. The variability observed between sites appears to overwhelm any obvious differences between trail and nontrail responses. Paired differences (trail-nontrail values for each site in Table 1) also do not display a consistent response except for a relative increase in the number of krummholz patches along trails.

**Table 1.** Change in patch and segment measures (1945-1991) for trail and nontrail areas.

	% area		<i>Patch measures</i>				<i>Segment measures</i>			
	trail	nontrail	edge density (m/m <sup>2</sup> )		# of patches		% segment length		# patches bisected	
	trail	nontrail	trail	nontrail	trail	nontrail	trail	nontrail	trail	nontrail
<b>Krummholz</b>										
Bear Valley	2.89	8.73	0.005	-0.020	7	-7	0.08	9.36	-1	1
Logan Pass	-0.66	-1.59	0.101	0.051	10	-13	-2.37	-3.32	-2	-5
Swiftcurrent	-1.06	-4.21	0.020	0.022	12	-1	-2.37	-4.66	6	3
<b>Patch Forest</b>										
Bear Valley	4.09	17.18	-0.103	-0.056	2	-14	2.05	19.04	4	-5
Sperry Chalet	-8.42	-9.68	0.068	0.148	-8	16	-2.78	-4.69	-2	0
Swiftcurrent	0.03	4.08	-0.035	-0.063	-3	14	0	6.79	0	4
Heavens <sup>1</sup>	1.74	1.24	0.052	0.048	23	14	5.03	0.57	5	3

<sup>1</sup>Heavens Peak is a control site.

### Statistical Interpretation

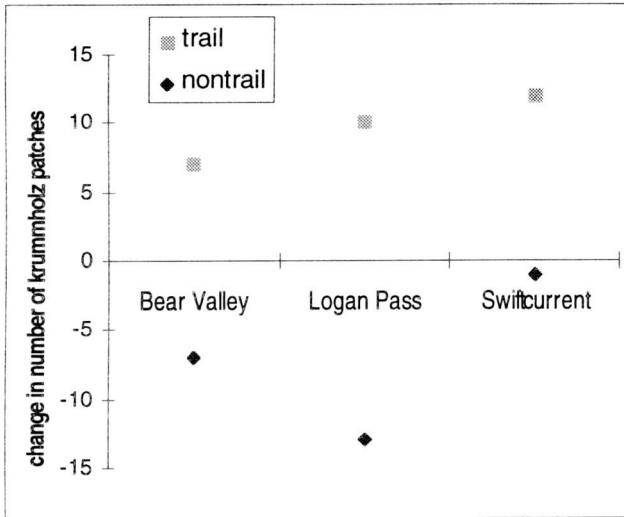
A statistically significant, consistent pattern of change in percentage area or edge density was not observed, as seen in Table 2. Although the expected response along trails relative to nontrail segments was less areal expansion of patch forest and krummholz, there was no evidence of such an effect. Change in percentage of segment through krummholz or patch forest and the number of patches bisected by a segment also did not exhibit a consistent response (Table 2).

**Table 2.** Statistical significance (one-sided p-values) of change (1945-1991) at trail compared to nontrail sites<sup>1</sup>. **Overall difference** values represent a trail effect after accounting for site variability (across both habitat types; from ANOVA, extra sum-of-squares F-test). **By habitat** values represent a trail effect and are grouped by habitat type (from Mann-Whitney Rank-Sum test).

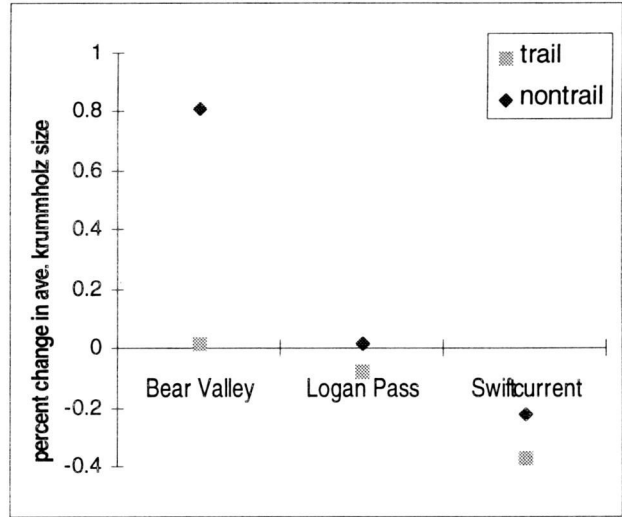
	<i>Patch measures</i>			<i>Segment measures</i>	
	% area	edge density (m/m <sup>2</sup> )	# of patches	% segment length	# patches bisected
<b>Overall difference</b> df=1,4	0.85	0.89	0.23	0.49	0.52
<b>by habitat</b>					
<b>Krummholz</b>	0.26	0.41	0.03	0.26	0.41
<b>Patch forest</b>	0.41	0.41	0.26	0.26	0.41

<sup>1</sup> Heavens Peak, control site, not included in p-value calculations.

Change in the number of patches did not exhibit a significantly consistent response for all sites and habitats combined, after accounting for site variability (Table 2). No consistent effect of trails was found in patch forest alone. In krummholz alone however, the number of patches increased at all sites with trails relative to sites without trails, as shown in Figure 4. Fragmentation of krummholz is suggested to result from human use on and near trails. Given that only three sites contained krummholz, any conclusions drawn must be treated with caution. However, additional support comes from the facts that krummholz edge density increased more along trails compared to sites without trails (at two of the three sites, Bear Valley and Logan Pass, as seen in Table 1), average size of krummholz patches along trails decreased compared to size of patches not along trails (Figure 5), and there was no consistent or significant increase in krummholz area along trails relative to nontrail sites (Table 1).



**Figure 4.** Increase in number of krummholz patches (1945-1991) for sites with trails compared to sites without trails.



**Figure 5.** Decrease in average krummholz patch size (1945-1991) for sites with trails compared to sites without trails.

### Other Data Trends

Heavens Peak, the control site with two nontrail segments, provides one means of identifying how much variability is to be expected given existing natural variability and the methodology used. The magnitude and direction of change observed for all measures of patch forest at Heavens Peak were comparable to other sites, suggesting that site variability overwhelmed an effect from trails.

Differences in response measures which might be correlated with site variability (area of wet meadow/dwarf shrub in 1945, area of dry meadow in 1945, or average patch size in 1945) were not found through exploratory analysis. Although to ensure that the changes observed were representative, replication of nontrail areas is recommended.

Patch forest was the habitat type which exhibited the greatest change from 1945 to 1991, at both nontrail and trail sites. However, this did not necessarily translate into an effect of trails compared to nontrail sites. Less overall change was observed at krummholz habitat types at both nontrail and trail sites. Yet the number of discrete

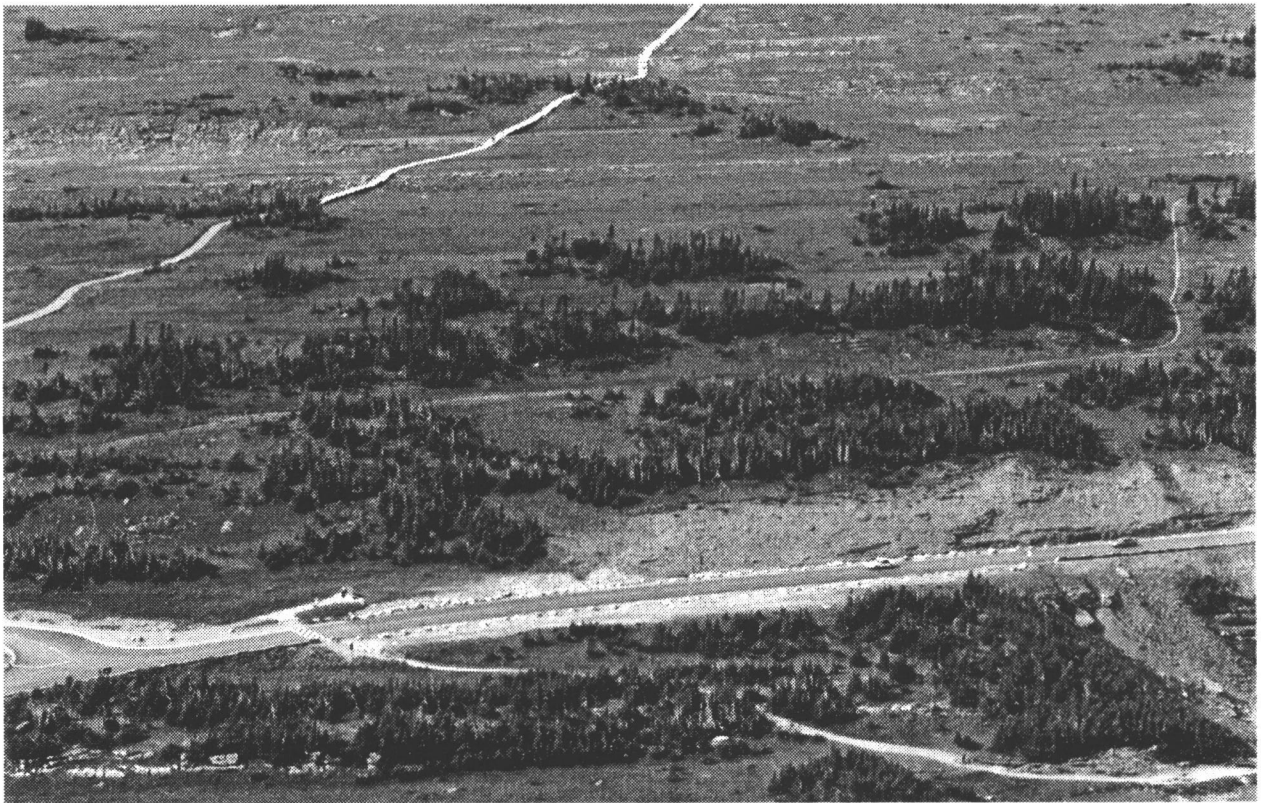
patches was the only consistent measure of a difference between nontrail and trail sites. There was no reason to suggest that conversion of krummholz to patch forest or patch forest to open forest was precluded by trails.

### **Observations from Photography**

Differences in the base print photography (1945 and 1991) initially suggested that significant changes in vegetation morphology have occurred throughout the alpine treeline region. However, comparison of the same sites using oblique photography and classified vegetation maps does not necessarily support such dramatic conclusions. Thus, detection of change based on paired regions within a single photograph was a necessary control for differences in the photography.

The aerial photographs in this analysis were from 1945 and 1991. Observations of both the aerial photos and classified images suggest that the effect of trails is limited to areas immediately adjacent to trails or areas of intense human activity. Longer term comparisons of vegetation change in Glacier National Park are available using terrestrial photos and archival documents. Survey photographs from construction of the Going-to-the-Sun Road at Logan Pass in 1927 reveal a narrow trail winding through well-spaced, sparse krummholz. Compared with a repeated photograph from 1997 (Figure 6), krummholz has become more dense yet not merged into a single stand where trails have been maintained or established.





**Figure 6.** 1927 (top) and 1997 (bottom) photos of Logan Pass vegetation. Note the change in trail location(s) and the proximity of adjacent krummholz. 1927 photo courtesy Glacier NP archives.

## **DISCUSSION**

### **Photography and Paired Sites**

Use of paired sites provided a baseline of "natural" change for comparison with change in areas where human activity is known to occur. In the context of this study, aerial photography was best suited for identification of the cumulative effects from years of varied human activity. This study attempted to identify effects of trails on krummholz and patch forest at distances beyond what is known to occur from trampling. However, the strength of the conclusions which can be drawn from the data are limited due to the numerous potential sources of variation which cannot be entirely accounted for using only photography. Furthermore, the ability to identify tree morphology from black-and-white aerial photography is limited by the scale, resolution, and spectral sensitivity of the film used. Error in image rectification also necessitates a cautious interpretation.

### **Effects of Trails**

Potential mechanisms for human activity affecting change in the spatial distribution of krummholz and patch forest at alpine treeline were identified, and changes in the spatial distribution of this vegetation were measured from relatively small scale (1:24,000) black-and-white aerial photography. With a relatively slow rate of change and short time frame evaluated (46 years), pronounced changes in vegetation are those most likely to be identified from photography. Such changes were not observed, and the expansion of krummholz and patch forest (as measured by area, edge density, and segment proportions) was not found to be inhibited along trails. The suggested mechanisms for affecting change have not necessarily been refuted, but rather are not evident at the spatial and temporal scale evaluated. Other studies have

identified the importance of altered forest understory vegetation along trails (Cole, 1978; Weaver et al., 1979), yet such effects are not likely to be identifiable from aerial photography as used in this investigation.

Change in vegetation is site specific and exists without human influence. This "background" rate of change was not explicitly modeled in this study and may explain some of the variability observed. Fire can greatly alter growth rates and distribution of vegetation, yet Swiftcurrent Pass (burned in 1936) and Bear Valley (partially burned in 1967) did not exhibit discernible differences in areal expansion of krummholz and patch forest between nontrail and trail sites. An enlarged avalanche path in 1991 at Bear Valley (the only site with a clearly evident avalanche path) primarily affected the trail portion of the site. This avalanche path could explain a slight decrease in patch forest area for trail sites and a decrease in the proportion of trail segment through patch forest habitats.

Management activities have potential positive and negative effects on vegetation near trails. However, efforts by management to clearly define and maintain desired trails appear to be successful in limiting effects of trails on vegetation beyond their immediate vicinity. Logan Pass or Sperry Chalet, where asphalt leaching, oil, and PCP toxicity were possible causes of impacts, did not exhibit a measured difference between nontrail and trail sites. Although the long-term effect and spatial extent of these activities have not been determined, the intended concentration of human activity to the trail would likely limit the physical impacts of visitors and mitigate effects at the scale of this study. Continued documentation of the effort and success involved in limiting off-

trail activity and maintaining clearly defined areas is necessary to verify such conclusions.

### **Fragmentation of Krummholz**

The only response measurement which exhibited the predicted characteristics at all sites with trails (relative to areas without trails) was an increase in the number of krummholz patches. Seedling mortality and reduced growth rates resulting from physical disturbance by visitors are suggested as the most likely cause. From terrestrial photography (at Logan Pass between 1927 and 1997), social trails, shortcuts, and rerouted trails are evident around trails and provide a logical mechanism for fragmenting krummholz through trampling and direct contact. Relatively slow rates of growth and establishment for krummholz result in long-lasting effects of such activities, even after attempts to minimize the evidence of past trails.

The fragmentation of krummholz was identified within a 100-m buffer distance of trails. Identification of fragmentation could also be made through other means of monitoring, such as measuring distances between adjacent patches of krummholz in areas without trails for comparison with distances between krummholz patches along maintained and social trails. In this study, observations from both aerial and terrestrial photos suggest that krummholz patch size is increasing and smaller patches are merging into larger clusters through growth and establishment. Thus fragmentation of krummholz at sites with trails can be seen as maintaining or increasing heterogeneity, with physical implications even for such small areas. For example, snowpack accumulates around krummholz, temperatures are moderated within krummholz patches, and fire spreads more readily within continuous vegetation. Fragmentation of

krummholz also has biological implications as both plant and wildlife habitat requirements (patch size, shape, distribution, etc.) associated with krummholz environments vary among species. Yet if human activity is causing this fragmentation, then the changes accompanying such activity (e.g. soil compaction, altered species composition, etc.) would be distinct from natural mechanisms causing heterogeneity (Forman and Godron, 1986). Protection of ecosystems and biodiversity requires management at both large ( $>10^6$  ha) and small ( $<10^2$  ha) spatial scales (Peterson et al., 1997), and this analysis suggests that efforts to minimize the effect of trails in Glacier National Park have been successful across increasing spatial scales, while effects of human activity are evident at smaller scales.

### **Recommendations**

A quantitative means of analyzing changes in alpine treeline vegetation similar to those changes visitors have experienced is a desirable management capability. Continued monitoring of vegetation change in a variety of disturbed and undisturbed sites is necessary to accomplish this goal. Studies repeated over a longer time span than performed here will allow for effects of trails to become more evident. Improved data sources will also permit more accurate portrayal of existing vegetation. Geostatistical analysis (c.f. Rossi et al., 1992) of both vegetation and biophysical properties along trails would provide additional comparisons for identifying potential effects from human activity. Although in this study a trail network has been seen to afford increased accessibility into mountains, the hypothesized preclusion of krummholz and patch forest growth and regeneration by human activity was not convincingly evident from aerial photography repeated after 46 years.

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