Arctic, Antarctic and Alpine Research, Vol. 39, No. 2, 2007, pp. 297–308

Development of a Spatial Analysis Method Using Ground-Based Repeat Photography to Detect Changes in the Alpine Treeline Ecotone, Glacier National Park, Montana, U.S.A.

W. Roush†‡*
J. S. Munroe† and
*D. B. Fagre**

*U.S. Geological Survey, Northern Rocky Mountain Science Center, West Glacier, Montana 59936, U.S.A.
†Geology Department *and* Environmental Studies Program, Middlebury College, Middlebury, Vermont 05753, U.S.A.
‡Corresponding author.
will@kamutlake.net

Abstract

Repeat photography is a powerful tool for detection of landscape change over decadal timescales. Here a novel method is presented that applies spatial analysis software to digital photo-pairs, allowing vegetation change to be categorized and quantified. This method is applied to 12 sites within the alpine treeline ecotone of Glacier National Park, Montana, and is used to examine vegetation changes over timescales ranging from 71 to 93 years. Tree cover at the treeline ecotone increased in 10 out of the 12 photo-pairs (mean increase of 60%). Establishment occurred at all sites, infilling occurred at 11 sites. To demonstrate the utility of this method, patterns of tree establishment at treeline are described and the possible causes of changes within the treeline ecotone are discussed. Local factors undoubtedly affect the magnitude and type of the observed changes, however the ubiquity of the increase in tree cover implies a common forcing mechanism. Mean minimum summer temperatures have increased by 1.5°C over the past century and, coupled with variations in the amount of early spring snow water equivalent, likely account for much of the increase in tree cover at the treeline ecotone. Lastly, shortcomings of this method are presented along with possible solutions and areas for future research.

Introduction

Repeat photography is the process of locating the position from which an existing photograph was taken, occupying that photo-point, and taking a new photograph to create a photo-pair of the same scene (Rogers et al., 1984). This method can effectively document landscape change and has been employed since 1888, initially for monitoring glacial movement but more recently in broader applications (Harper, 1934; Rogers et al., 1984; Klett, 2004). Over the past 25 years numerous books and studies have used repeat photography to provide compelling qualitative information about the magnitude and type of long-term ecological and geological processes that would not otherwise be possible and have produced photo-pairs that are easily interpreted by a broad audience (Rogers, 1982; Gruell, 1983; Vale and Vale, 1983, 1994; Klett et al., 1984; Baars et al., 1994; Webb, 1996; Fielder et al., 1999; Butler and DeChano, 2001; Klasner and Fagre, 2002; Rhemtulla et al., 2002; Munroe, 2003; Klett, 2004).

While ground-based repeat photography can effectively display qualitative landscape change, it has rarely been used to measure quantitative change, largely because an oblique perspective creates a continuously varying scale and prevents linking landscape features in the photograph to absolute spatial coordinates. Detailed quantitative measurements of landscape processes and changes can be made from airborne and space-borne platforms. However, systematic aerial photographic surveying only began ca. 1950, while satellite images only became available in the 1960s. Furthermore, both the methods used in, and results of, analysis of aerial photography and satellite images are often not easily understood by the general public. In contrast, ground-based photographic records extend as far back as the 1860s and are a universally familiar medium. The development of new methodologies capable of extracting meaningful, quantitative information from historical photographs would provide a technique for addressing questions of landscape change as well as a way to record and measure responses of landscapes on a longer time scale than those offered by satellites and other modern equipment.

Earlier efforts to extract quantitative information from ground-based photography include Hofgaard et al. (1991) and Kullman (1987), who repeated photographs of individual trees to measure tree fitness and growth during the intervening period. More recent studies have developed methodologies to quantitatively document landscape change. Notable among these are the use of on-screen sampling of vegetation in photo-pairs to determine percent change in vegetative cover in the Uinta Mountains, Utah (Munroe, 2003) and development of a GIS method that digitized polygons based on vegetation type and used a transition matrix to document vegetation changes in the montane zone of Jasper National Park, Canada (Rhemtulla et al., 2002).

The alpine treeline, defined here as the broad ecotone stretching from the end of full canopy forest to isolated krummholz patches, is an excellent landscape feature for use in further development and testing of these techniques for several reasons. First, abrupt and clear distinctions between plant communities makes changes in the treeline ecotone easier to detect visually than in other transitional environments. Second, the treeline ecotone is a dynamic environment responding to a variety of environmental factors (Cairns, 1990; Holtmeier, 2003), ensuring there will be landscape changes detectable by repeat photography. Finally, because significant ecological changes in alpine plant communities take place over longer time scales than most field studies, quantified repeat photography is one of the few

1523-0430/07 $7.00

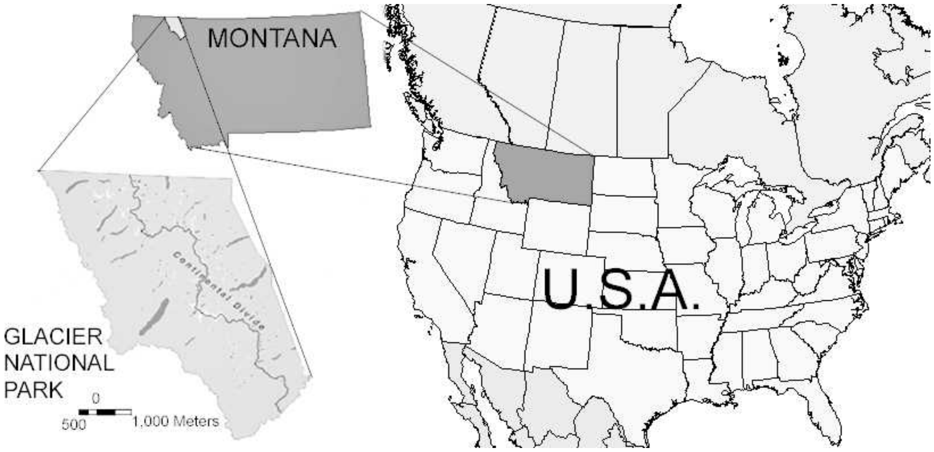


FIGURE 1. Location of Glacier National Park. Latitude and longitude are given in Figure 2.

ways to document change and increase our understanding of treeline ecotones.

Our study had two objectives: (1) to develop a method for quantitative analysis of repeated photographs, and (2) to apply this method to the treeline ecotone of Glacier National Park (GNP), Montana, to examine vegetation changes over multi-decadal timescales. Treeline change in GNP has been documented (Butler et al., 1994; Cairns and Malanson, 1997, 1998; Butler and DeChano, 2001; Cairns, 2001; Klasner and Fagre, 2002), but these previous studies could be augmented both temporally and spatially by using historical photographs taken during the last century. Here we describe a new method applying ArcGIS software (ESRI, 2002) to digital photo-pairs that allows vegetation change to be categorized and quantified. The patterns of tree establishment identified in GNP are described, and the possible causes of changes at the treeline ecotone are discussed. Finally, shortcomings of this method are presented along with possible solutions and areas for future research.

STUDY AREA

Comprehensive photographic archives, extensive documentation of paleoclimates and past human interactions with the landscape, and considerable prior research on alpine and subalpine environments make GNP an ideal study area for repeat photography. GNP occupies 4075 km^2 in northwestern Montana (Fig. 1), where elevations range from 948 to 3290 m a.s.l. (Shaw and On, 1979; Rockwell, 2002). Steep topography, climatic fluctuations, and past glaciations have created a treeline that is much more spatially variable than that occurring in the southern Rocky Mountains (Cairns and Malanson, 1997). Becwar and Burke (1982) used topographic maps to estimate that 80% of the forest-tundra transition spans an elevation range of 550 m in GNP, compared to 150 m in the southern Rocky Mountains.

The area that is now GNP was protected as a forest reserve prior to 1910, when the limited human impact in the area was further reduced by the establishment of the park. The area was never commercially logged, and grazing has been largely limited to horses used for pack trips (Shaw and On, 1979; Vogler, 1998). During the 1930s an outbreak of whitebark pine blister rust in high elevation sites infected whitebark pines (*Pinus albicaulus* Engem.) and by the 1950s had killed most of these trees (Kendall and Keane, 2001). Recent human impact in alpine areas of GNP is minimal and is largely due to trail use and maintenance. Probably the greatest direct human impact on vegetation in GNP has been a policy of fire suppression over the past 80 years that has contributed to increased forest cover and reduced early successional habitats. This policy now allows some fires to burn for wildland benefit. Fires occasionally burned into alpine areas in the past and may have affected treeline ecotone dynamics (Arno, 2001). Study sites for this project were located within the treeline ecotone both at the extreme upper limit of trees and in open subalpine meadows at slightly lower elevations. Topography at the sites varied from gentle meadows to steep rocky hillsides. The dominant treeline species at all sites is subalpine fir (*Abies lasiocarpa* [Hook.] Nutt), with isolated instances of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). Observed treelines were both orographic and altitudinal as defined by Holtmeier (2003).

Methods

SELECTION OF HISTORICAL PHOTOGRAPHS

The historical photographs replicated for this study were obtained from GNP's archive and were taken by three early 20th century photographers: George Grant, Tomer J. Hileman, and Fred Kiser. The collection of photographs from which selections were made was extensive and contained views from throughout the park, although particularly scenic or easily accessible views are more common. Approximately 2000 photographs were examined before final selections were made. Photographs were selected based on several criteria. First, the images needed to be of high quality and to clearly document the treeline ecotone. Second, photographs were selected with the goal of isolating climate as the primary factor that would cause a change in the characteristics of the treeline ecotone shown in the photograph. Third, photographs of a hillside of roughly constant slope that extended above a non-orographic treeline were preferred. Album prints of 17.5 × 26.5 cm (8 × 12 in.) were scanned at 273 dots per cm [600 dots per inch (DPI)], and saved as Tagged Image File Format (TIFF) files. Printed copies were used in the field to locate historic photo-points.

LOCATING HISTORICAL PHOTO-POINTS

To locate the sites from which historical photographs were taken, information accompanying the photographs or prominent landmarks in the view were used to find the general area on a topographic map. To determine the precise location of photo-points in the field, the principle of parallax was used to find lines of equal perspective and proportionate length between features (e.g. background ridgeline intersections and permanent fore-

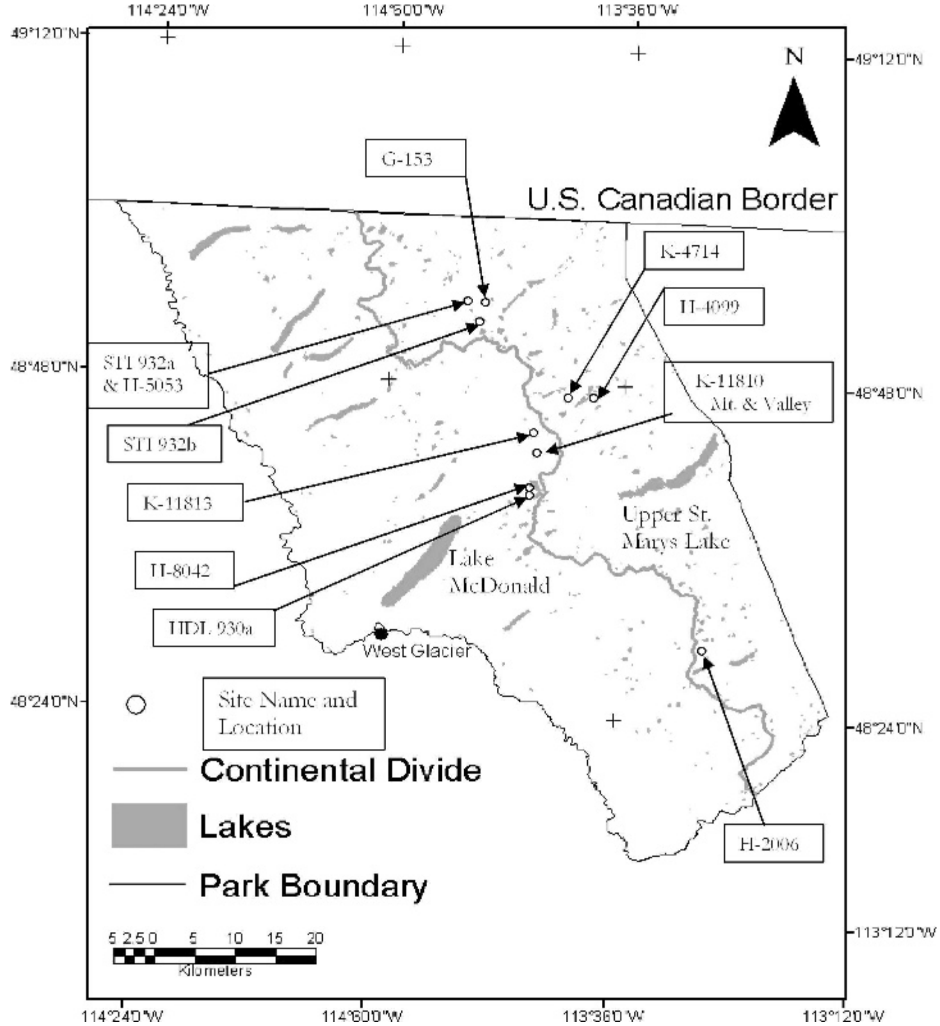


FIGURE 2. Locations of the 12 sites which were rephotographed in Glacier National Park. See Table 2 for site details.

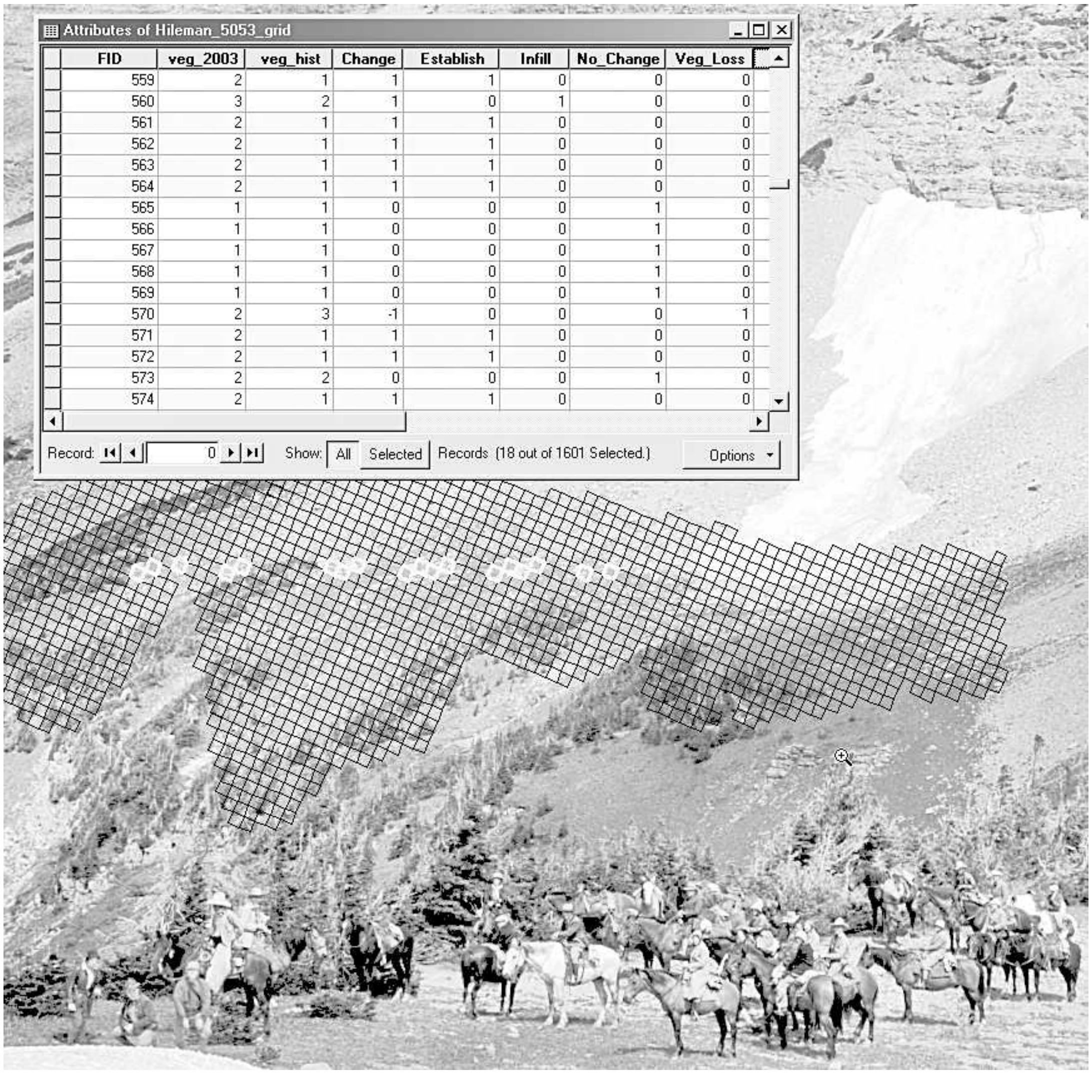
ground objects, such as boulders) in the historical photograph and the present landscape (Rogers et al., 1984). Photo-points were located to within ~20 m using background features, then adjusted to within ~1 m of the original point using foreground features. In a few photo-pairs new vegetation obscured the view shown in the historical photograph, so the modern photograph was taken from a slightly different location (<2 m away). Figure 2 shows the locations of all photo-points included in this study.

A Nikon F-100 35 mm single lens reflex camera with a 24–200 mm f3.5 Nikon lens was used to shoot Kodak technical-pan black and white film at an ASA of 12. For each historical photograph site, 12 frames were taken with bracketed exposures; 6 of these used a Yellow 12 filter to increase contrast. The location of each photo-point was recorded using both a GPS unit and a topographic map. Camera height and bearing as well as aperture, shutter-speed, and focal length were also recorded.

ANALYSIS OF PHOTO-PAIRS

Of the 12 modern negatives per photo-pair, the image with exposure and contrast values which most closely matched the historical image was selected for comparative analysis. All modern negatives were converted to TIFF files by scanning at 1820 dots per cm (4000 DPI). To quantitatively analyze change between the modern and historic image files, an original method was developed using ArcGIS software (ESRI, 2002). First, the paired image files were imported into ArcMAP and ortho-referenced to each other using a minimum of five common points with the majority of these located in the vicinity of the area to be analyzed. This step ensured that the scales of the two images were equal and that they were overlain exactly in ArcMAP's spatial system. Second, an ESRI "fishnet" script (ESRI, 2002; Nicholas, 2003) was used to create a grid overlying the area of interest. Each cell of the grid is an independent polygon (Fig. 3), and information about what lies under each grid cell can then be used to populate a table corresponding to the grid in a spatially explicit manner. The grid was scaled to vegetation features depicted in each photo-pair, and because the scale of each photo-pair and corresponding grid varies depending on the distance of the subject from the photo-point, the amount of ground covered by each cell differs among photo-pairs. Thus, only relative changes can be measured between photo-pairs. Additionally, within a photo-pair, foreground space will occupy a larger area in the image than background space. To mitigate this issue, the area chosen for analysis in each photo-pair was held to a roughly constant distance from the photo-point.

Third, the grids scaled to each photo-pair were digitally overlain on the images, and cropped to the area from which cell-by-cell changes were to be measured. An attribute table was created for each grid file, with fields containing information regarding the vegetation visible in each cell (Fig. 3). Each cell received a value of 1, 2, or 3 indicating bare ground, partial tree cover, and complete tree cover, respectively. This information was then used to create mutually



Attributes of Hileman_5053_grid

FID	veg_2003	veg_hist	Change	Establish	Infill	No_Change	Veg_Loss
559	2	1	1	1	0	0	0
560	3	2	1	0	1	0	0
561	2	1	1	1	0	0	0
562	2	1	1	1	0	0	0
563	2	1	1	1	0	0	0
564	2	1	1	1	0	0	0
565	1	1	0	0	0	1	0
566	1	1	0	0	0	1	0
567	1	1	0	0	0	1	0
568	1	1	0	0	0	1	0
569	1	1	0	0	0	1	0
570	2	3	-1	0	0	0	1
571	2	1	1	1	0	0	0
572	2	1	1	1	0	0	0
573	2	2	0	0	0	1	0
574	2	1	1	1	0	0	0

Record: 0 Show: All Selected Records (18 out of 1601 Selected.)

FIGURE 3. Attribute table and associated grid overlain on study site Hileman 5053. Each cell has a unique identifier (FID). Information regarding historical and modern vegetation as well as the calculated type of vegetation change populates the table.

exclusive categories (no change, vegetation loss, infilling, and establishment) describing the type of tree cover change occurring within each grid cell. No change indicates no visible difference in the cell between the two photographs; vegetation loss is defined as a decrease in visible vegetative cover in the modern photograph; infilling is defined as increased or denser vegetation in areas which showed sparse vegetation in the historical photograph; and establishment is defined as new vegetation in areas which showed bare ground in the historical photograph (Table 1). It was not possible to determine the absolute change in tree cover documented in the photo-pairs because of the continuously varying scale created by the oblique perspective and the complex topography.

Finally, to evaluate the effect cell size had on the analysis, two photo-pairs were resampled with a new grid, the cell size of which was four times larger than used in the first analysis, and these results were compared to the original analysis.

Results and Discussion

Thirty-two historical photographs were replicated in July and August 2003. Of these, 11 (showing 12 sites) were suitable for analysis because they had good lighting, readily distinguishable vegetation features, and areas which appeared not to have burned. The time span represented by the photo-pairs ranged from 71 to 93 years (mean= ~75) (Table 2). The most notable trend illustrated by the photo-pairs is a change in percent tree cover, which increased in 10 out of 12 photo-pairs (Table 2), with a mean increase of 60% (Range: −4% to 366%; Standard Deviation (S.D.)

TABLE 1

Definitions of cell types showing categories of tree cover change.

Category of Tree Cover Change	Tree Cover Change between Historical and Modern Photographs
No change	Historical value = Modern value
Vegetation loss	Historical value > Modern value
Infilling	Historical value = 2 (some tree cover), **and** Modern value = 3 (complete tree cover)
Establishment	Historical value = 1 (bare ground), **and** Modern value = 2 or 3 (some tree cover or complete tree cover)

TABLE 2

Relevant information for each site analyzed.

Photo-pair	Change in Tree Cover (%)*	Location	Elevation (m)	Aspect	Date of Historical Photograph	Historical Photographer	Date of Modern Photograph	Modern Photographer	Coordinates of Photo-point (Lat., Long.)
Kiser 4714	−4	Castle Mountain	2135	South	1910	Fred Kiser	20 Jul 2003	William Roush	48°49.192′N 113°44.485′W
Grant 153	−2	Mokawantas Junction	2025	South	1932	George Grant	21 Aug 2003	William Roush	48°52.166′N 113°48.581′W
Kiser 11810 Valley	6	Haystack Mountain	1980	South	Pre-1925	Fred Kiser	22 Aug 2003	William Roush	48°43.384′N 113°43.273′W
Hileman 2006a	11	Pitimakan Pass	2100	West	1931	Tomer J. Hileman	26 Jul 2003	William Roush	48°31.070′N 113°27.441′W
Hileman 4099	13	Lake Josephine	2100	Northwest	ca. 1930	Tomer J. Hileman	19 Jul 2003	William Roush	48°47.339′N 113°40.816′W
Kiser 11813	16	Granite Park	2075	Southwest	Pre-1925	Fred Kiser	17 Jul 2003	William Roush	48°46.222′N 113°46.279′W
STI 932b	35	Atsina Lake Basin	2000	Southwest	1932	Tomer J. Hileman	19 Aug 2003	William Roush	48°52.855′N 113°51.898′W
Kiser 11810 Mtn.	44	Haystack Mountain	2225	South	Pre-1925	Fred Kiser	22 Aug 2003	William Roush	48°43.384′N 113°43.273′W
STI 932a	47	Stoney Indian Lake	1950	Northwest	1932	George Grant	19 Aug 2003	William Roush	48°52.908′N 113°51.865′W
Hileman 5053	64	Stoney Indian Pass	2105	Northeast	ca. 1930	Tomer J. Hileman	19 Aug 2003	William Roush	48°52.885′N 113°51.931′W
HDL 930a	128	Hidden Lake	2010	Northeast	1930	Tomer J. Hileman	28 Jul 2003	William Roush	48°40.930′N 113°44.418′W
Hileman 8042	366	Hidden Lake	1980	Northwest	ca. 1930	Tomer J. Hileman	28 Jul 2003	William Roush	48°41.065′N 113°44.439′W

* Shows a summary of percent increase in cells with any vegetation in the photo-pairs. Note, this does not include areas that changed from partly covered to completely covered (thus Grant 153 shows a decrease in percent change despite the total number of grid cells which increased in vegetation being larger than those which lost vegetation as shown in Table 3). Instead, this variable measures the percent increase of ground having any tree cover.

= 103%). Excluding the two sites (Hileman 8042, and HDL 930a) in which tree cover increased most dramatically, the mean is 23% (S.D. = 23%).

Tree establishment was documented in all photo-pairs, including the two that showed an overall loss in tree cover (Table 3). Infilling occurred in all sites except Kiser 4714, though overall in lesser amounts. Establishment and infilling appear to be inversely related. The greatest infilling occurred at two sites (Kiser 11813 and Hileman 2006a) with low establishment values, and the highest establishment values occurred at sites (Hileman 8042 and HDL 930a) with low amounts of infilling (Table 3).

TABLE 3

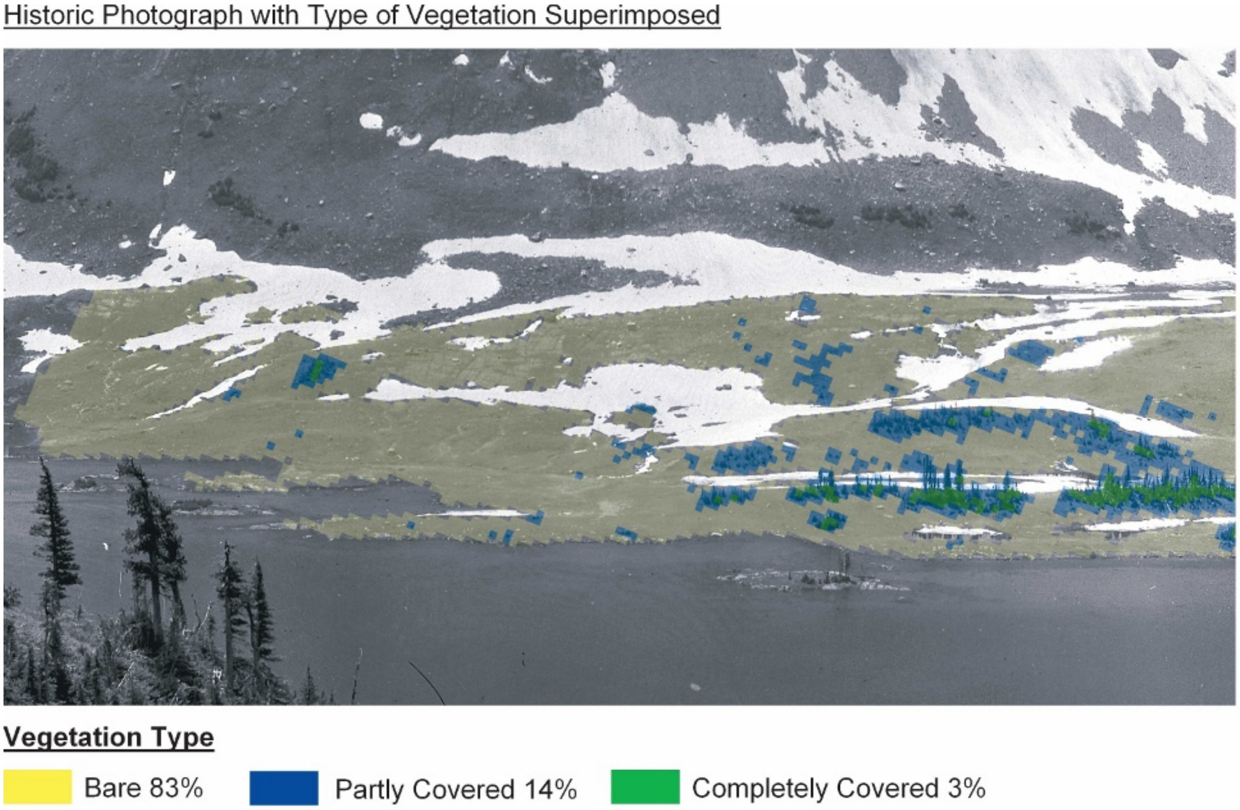
Percent of cells showing establishment, infilling, vegetation loss, and no change in each photo-pair. Sites are ordered by percent establishment.

Site Name	Establishment (%)	Infilling (%)	Vegetation Loss (%)	No Change (%)
Grant 153	5	8	7	79
Kiser 11810 Valley	5	11	4	81
Kiser 4714	10	0	24	63
Hileman 2006a	11	37	8	44
Hileman 4099	12	7	11	70
Kiser 11813	14	41	5	40
Kiser 11810 Mt.	21	4	3	71
STI 932b	23	18	1	58
Hileman 5053	24	6	8	63
STI 932a	28	23	5	44
HDL 930a	47	8	10	35
Hileman 8042	62	11	0	27
Average	22	14	7	56

The method developed for this project introduces quantitative rigor to the assessment of landscape change documented by photo-pairs and reduces subjective evaluations or a preferential focus on obvious changes in landscape elements. When applied to the alpine treeline ecotone of GNP, this method identified the magnitude and direction of vegetation change, the type of change (no change, vegetation loss, infilling, and establishment), and spatial distribution of change. In the following discussion, three separate photo-pairs that illustrate different spatial patterns of vegetation change are described, along with possible causes for these changes.

PHOTO-PAIR HILEMAN 8042

This photo-pair illustrated the most dramatic expansion of trees into a meadow environment, likely as a result of several factors that make this site ideal for tree growth and establishment (Fig. 4). First, stands of mature trees located just to the north (right) of the study site provide a substantial and proximal seed bank. Second, the physical environment at this site appears generally favorable for tree growth, as exemplified by the trees in the original Hileman 8042 photograph. Despite their location immediately below the upper treeline, these trees have a growth form more typical of those in lower elevation, mature forests. In contrast, other historical photographs show trees in krummholz forms or as isolated tree patches that are often located below cliffs and on more exposed mountainsides where winter desiccation and ice abrasion are greater impediments to upright tree growth (Holtmeier, 2003; Malanson et al., in press). Finally, the ground at this site is flat to gently sloping and includes many minor topographic highs, which Butler et al. (2003) observed to have



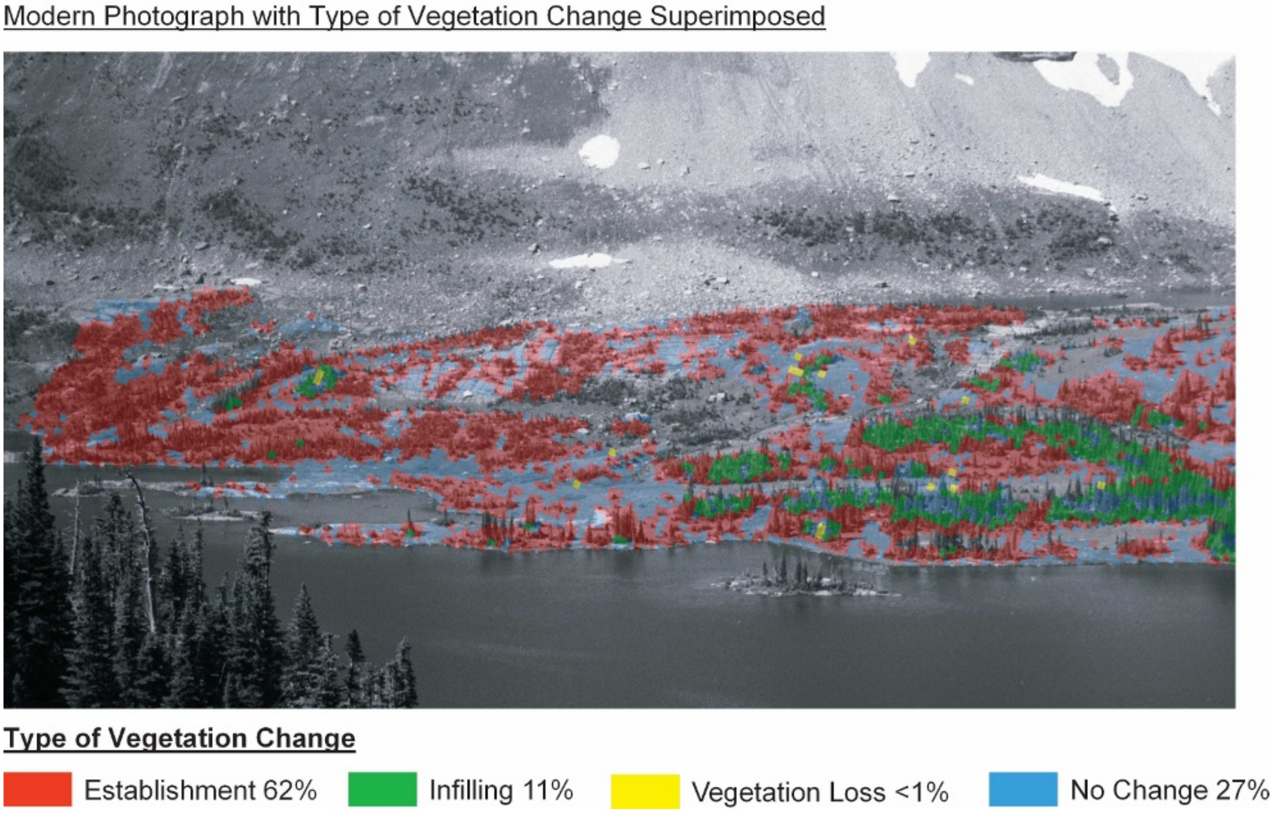


FIGURE 4. Detail of photo-pair Hileman 8042 showing vegetation type superimposed on the historical photograph and the type of vegetation change superimposed on the modern photograph. Note the massive invasion of trees across the entire photograph.

a strong influence on tree position by providing well-drained soil that increases establishment.

PHOTO-PAIR HILEMAN 5053

The treeline in the photo-pair Hileman 5053, located at the base of a scree slope and near the upper elevation of tree growth, provides an example of two controls acting in unison on the treeline at a single location (Fig. 5). The photo-pair shows that the upper limit of tundra has not changed perceptibly in the intervening 72 years, suggesting that tundra vegetation is unable to colonize the talus. Upright trees however, have clearly expanded their range (approximately 10–20 vertical m), with some now occupying the upper limit of all vegetation at this site. It is possible that the functional treeline at this site may be depressed due to the presence of the talus, which is hypothesized to be the second largest control on treeline in GNP after climate (Cairns, 2001). This notion is supported by the presence of upright trees within the upper portion of the treeline ecotone at this site. Thus, the combined effect of tree establishment and infilling, and the inability of alpine meadow species to colonize the active talus, has caused a marked decrease in tundra area at this site while the density of trees has increased.

The majority of the infilling and establishment in this photo-pair occurred along the edges of historical vegetation and may be a result of existing trees improving conditions for establishment in their immediate environment by altering soil characteristics and microclimates (Stevens and Fox, 1991; Holtmeier, 2003; Holtmeier and Broll, 2005). Specifically, establishment was concentrated in the three tongues of meadow that reach down into the trees in the historical photograph (Fig. 5). It is not possible to determine the direct cause of the observed vegetation change from the photo-pair alone. However, the distinct spatial pattern related to distance from both the talus and historical tree clumps suggests that protection from wind plays a role in the spatial variability of tree establishment within the treeline ecotone as was observed by Resler (2006) on Lee Ridge in GNP.

PHOTO-PAIR KISER 11813

The change seen in photo-pair Kiser 11813 is notable because 61% of the grid cells record change (Fig. 6), but this occurred largely as infilling (41%), with a relatively low level of establishment (14%). Tree growth proceeded outward from the lower center of the site, where trees were densest in the historical photograph. The small amount of establishment occurred primarily on the rising slope at the left side of the site and represents an overall altitudinal increase of 5–10 m. Most notable is the disappearance of the ribbon forests present in the historical photograph. This forest type is thought to be caused by underlying bedrock topography (Butler et al., 2003) creating topographic highs and depressions in the landscape. The observed change indicates that the factors which caused the infilling of the ribbon forest are powerful enough to overcome geologic controls on tree location.

GENERAL TRENDS AND INTERPRETATIONS

The most common trend documented by the photo-pairs is an increase in tree cover, both as infilling and establishment. Establishment occurred up to hundreds of meters away from historical vegetation, and half the sites experienced a 35% or greater increase in total tree cover. Even in the two sites where overall tree cover decreased, localized establishment and infilling occurred. Local factors certainly play a significant role in determining the magnitude of change that occurs at any given site (Holtmeier, 2003), yet the ubiquity of the observed changes indicates there is a more universal forcing mechanism that is amplified or attenuated by local conditions. Previous studies have documented an increase in tree establishment in subalpine forests in response to increased growing season temperature (Kullman, 1991; Rochefort et al., 1994; Cairns and Malanson, 1998; Kusnierczyk and Ettl, 2002; Lloyd et al., 2002), while Hofgaard et al. (1991) and Kullman (1991) in Scandinavia, and Rochefort et al. (1994) and Hessl and Baker (1997) in the American and Canadian Rockies, found a strong correlation between increased tree growth at treeline and rising summer temperatures. Data from the Kalispell WSO AP Station, part of the Historical Climate Network (Easterling et al., 1996) reveal that while the yearly mean temperature has increased only a small amount since 1900 (about 0.5°C), minimum summer temperatures have increased about 1.5°C in the past century (Fig. 7), lengthening the growing season by increasing the number of frost-free days. Watson et al. (in press) show a similar or greater increase in minimum spring and summer temperatures from 15 temperature stations along the continental divide. Butler et al. (1994) noted that increases in tetraterm temperatures (average temperature of the period June to September) observed in GNP from 1984 to 1991 could be linked to seedling establishment. And in a summary of studies examining seedling establishment in the alpine tundra, Alftine et al. (2003) found tundra invasion by forests of the Pacific Northwest to be associated with warmer, drier periods. Together these types of climatic changes would improve the carbon balance for existing trees and make it easier for seeds to germinate and prosper. While establishing direct causality for increased tree growth is not possible from the photo-pairs alone, changes in climate occur at a large enough scale to have influenced tree establishment at all sites in this study. Thus, the rise in mean summer minimum temperatures over the past several decades (Fig. 7) is a possible explanation for the observed changes, with differences in the magnitude and nature of the observed change demonstrating the importance of site specific conditions.

Precipitation also affects tree growth and establishment but in more complex ways depending on whether water comes in the form of snow or rain (Holtmeier, 2003). Most of the precipitation at high elevations in GNP occurs as snow (Klasner and Fagre, 2002) and has more interannual variation than temperature (Fig. 7). Kusnierczyk and Ettl (2002) documented a positive correlation between non-growing season precipitation and tree growth, and given that cold soils and high winds are the largest limiting factors on tree establishment in continental climates, a deep snow pack would reduce these negative effects and aid tree establishment (Rochefort et al., 1994). The 10-year running mean of 1 May Snow Water Equivalent (SWE) from Flattop Mountain in GNP shows a marked increase during the period 1950–1975 (Fig. 7). This increase differs from the temperature record, which is fairly stable during this period and shows its most significant gains between 1915 and 1930 and again between 1970 and 1980 (Fig. 7). Selkowitz et al. (2002) demonstrated a link between longer term (20–30 yr) cycles of increased SWE within GNP and the negative phase of the Pacific Decadal Oscillation (PDO), and Alftine et al. (2003) found high levels of establishment occurring in the treeline ecotone of Lee Ridge in GNP during the negative phase (late 1940s to late 1970s) of the PDO. It is likely then that some of the establishment seen in the photo-pairs is a result of the increased snow levels during the period 1950–1975.

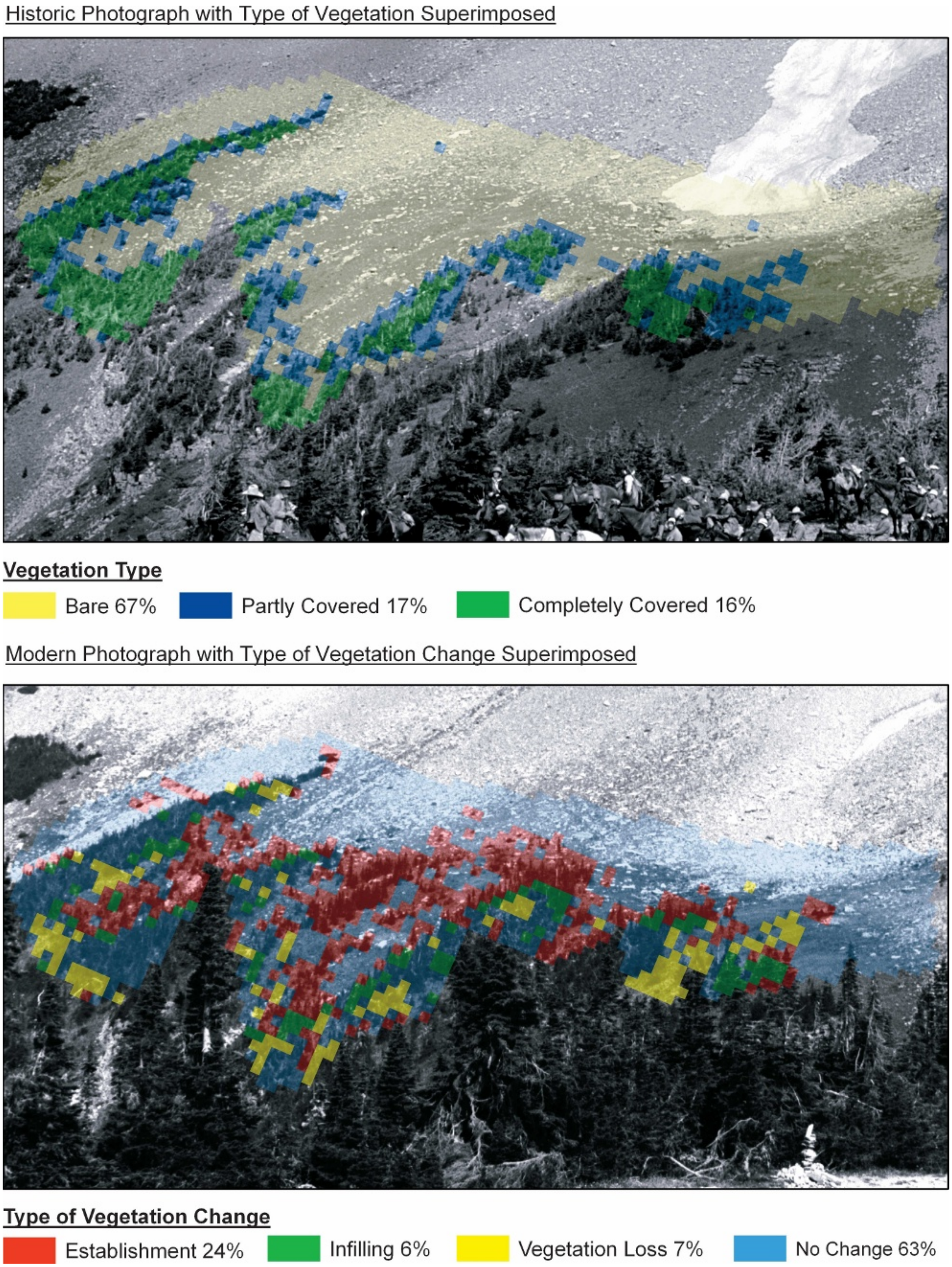
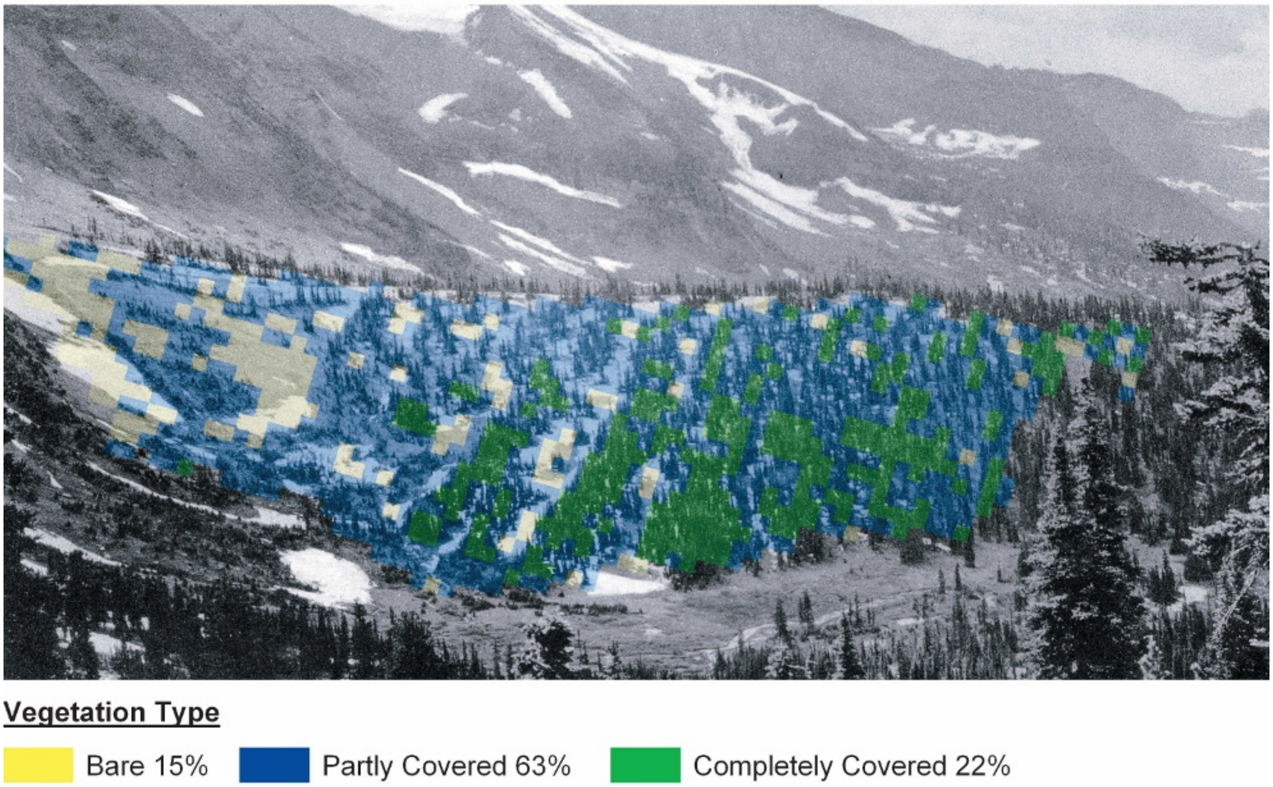


FIGURE 5. Detail of photo-pair Hileman 5053 showing vegetation type superimposed on the historical photograph and the type of vegetation change superimposed on the modern photograph. Note the disappearance of meadow below the talus and the preference of tree establishment to occur adjacent to historical vegetation in the three tongues of meadow which used to reach down into the forest.

Historic Photograph with Type of Vegetation Superimposed



Modern Photograph with Type of Vegetation Superimposed

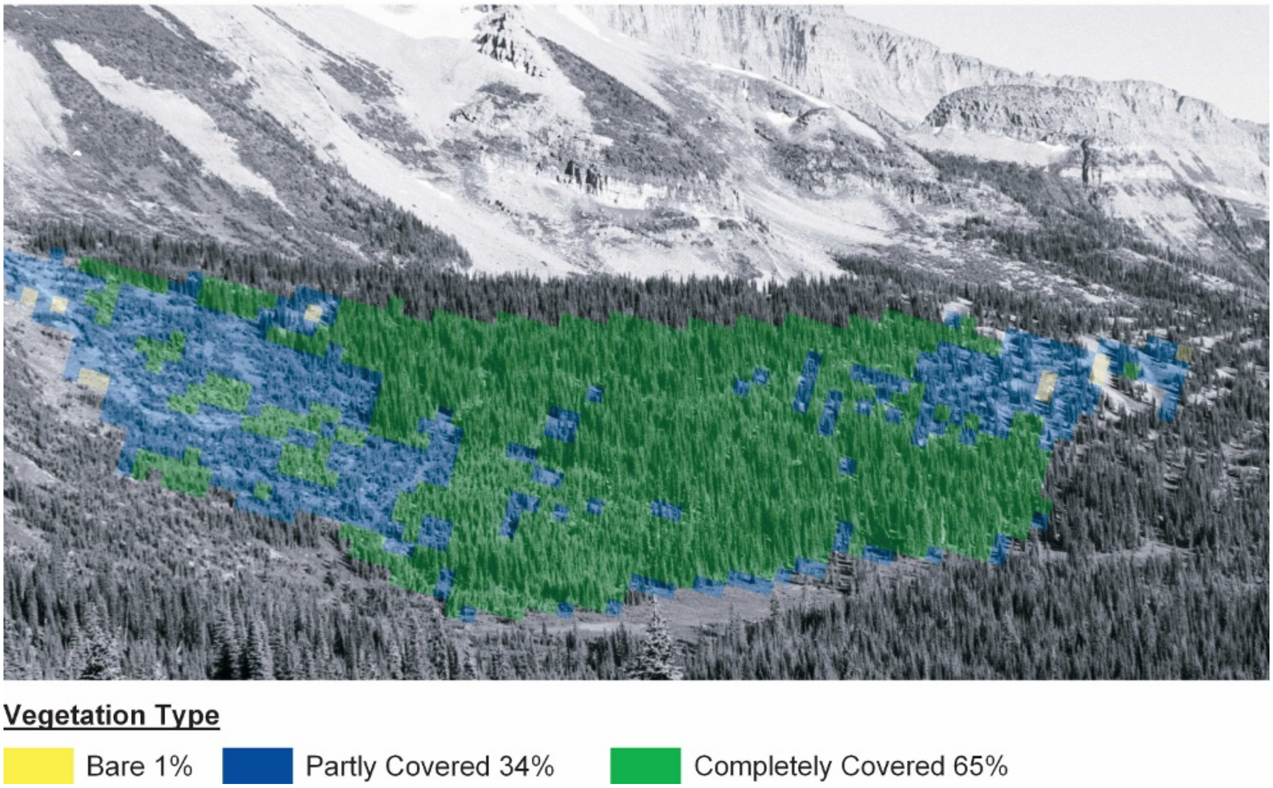


FIGURE 6. Detail of photo-pair Kiser 11813, showing vegetation type superimposed on both the historical and modern photographs. Note the disappearance of the ribbon forest environment present in the historical photograph and the slight upward movement of treeline on the far left side of the photograph.

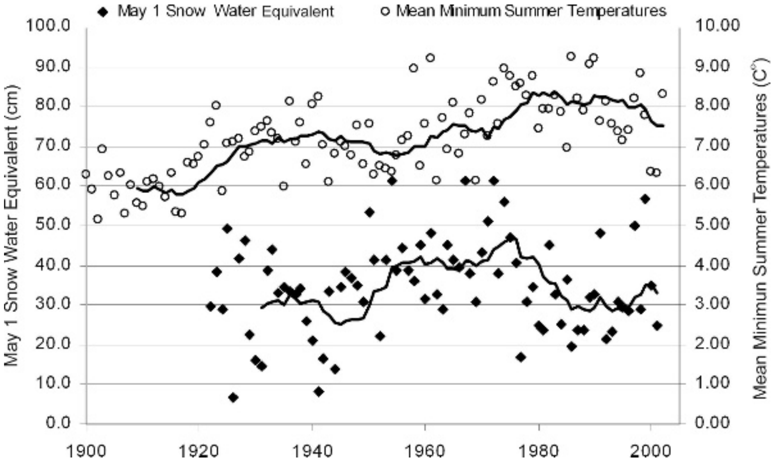


FIGURE 7. Annual spring snow pack (1 May Snow Water Equivalent) from Flattop Mountain and mean minimum summer (June–August) temperatures at the U.S. Historical Climatology Network's Kalispell WSO AP Station, 70 km from Glacier National Park. Black lines represent 10-year moving averages.

Consistent with other studies in GNP, photo-pairs from this study indicate that krummholz patches appear to have changed far less than upright trees at treeline or in the subalpine meadow environment. A rephotographic study by Butler et al. (1994) showed treeline position to have been quite stable throughout the park from 1972 to 1992, including krummholz patches that were exactly the same size in historical and modern photographs.

Photo-pair Kiser 11810, which includes two separate sites, underscores the complex interrelationships between altitude, growth form, precipitation, and exposure. Tree establishment was more than four times greater (Table 2) at the exposed mountain site where upright trees are present ~245 m above the sheltered, krummholz-dominated valley site. The valley site likely has a greater potential for excessive snow drifting, which has been negatively correlated with establishment by limiting growing season length and quality (Franklin et al., 1971) and by reducing the carbon balance of the trees (Cairns and Malanson, 1998). Other studies have shown that snow accumulation can benefit trees by protecting them from winter desiccation and injury (Walsh and Kelly, 1990; Cairns and Malanson, 1997; Hattenschwiler and Smith, 1999). In this case, it seems likely the valley site receives so much wind-deposited snow that the shortened growing season outweighs the sheltering effects of the winter snow pack and limits seedling establishment.

Finally, it should be noted that fire is not thought to be a major factor in causing the changes documented by the studied photo-pairs. Forest stand-age maps were consulted in selecting the historical photographs to eliminate the possibility that the changes documented in the photo-pairs were simply due to succession following a stand-clearing fire. These stand-age maps do not necessarily provide the level of detail necessary to identify less-extensive fires, but the effects of fire would be obvious in the photo-pairs. For instance, at one site—excluded from the final analysis—a fire occurred between the historical and modern photographs, resulting in a loss of tree cover in 73% of the grid cells and limiting tree cover increase to only 6% of the grid cells. Stand-age maps showed this site as having had no stand replacing fires in the past 200 years, yet evidence from the photo-pair was unequivocal. The thin bark of subalpine fir (the dominant treeline species in the photo-pairs) makes this species particularly vulnerable to high intensity fires (Alexander et al., 1990) and as a result, such fires leave considerable visual evidence in the landscape. Furthermore, while subalpine fir establishment does occur on burned areas, fire is not an essential part of the life cycle of this shade-tolerant tree (Alexander et al., 1990). Thus the observed establishment and infilling of subalpine fir does not require fire to create suitable habitat.

Shortcomings of the Applied Method

The method described in this paper improves our ability to detect landscape change using repeat photography, yet has limitations worth noting. The inability to determine scale within or among photo-pairs limits analysis to relative, rather than absolute, change and makes comparisons with other studies difficult. Within photo-pairs the continually varying scale between foreground and background areas requires that areas chosen for change analysis occupy a consistent distance from the photo-point. Relying on percentages to document change is also complicated by the size of the sampling area, as this will affect the values obtained. Similarly, if landscape features that will never be vegetated (e.g. lakes or cliff faces) are included in the study area, then the results will be biased toward a lack of landscape change.

Additionally, in an oblique view, prominent features may obscure parts of the landscape behind them. In cases where a tree branch covers bare ground it is necessary to decide whether to record the tree branch as vegetation or the ground behind it as bare ground. Thus, it is preferable for one person to conduct the analysis on all photo-pairs as was done in this study to maximize

TABLE 4

Effect of grid cell size on results obtained from analysis of photo-pairs. Values are percent of grid cells for each photo-pair. Note that the trends in the type of vegetation change (light gray) are preserved regardless of cell size, while the percent of cells with partial vegetation cover (dark gray) increases with cell size, and the percent of cells with bare ground or complete vegetation cover (white) decreases with cell size.

		STI 932		HDL 930b	
	Cell Size	Normal	4 Times Larger	Normal	4 Times Larger
Type of Vegetation Change	Establishment	28	17	42	41
	Infilling	23	17	25	29
	Vegetation Loss	5	1	0	0
	No Change	44	65	32	30
Historical Vegetation Cover	Bare	46	29	19	43
	Partly	46	66	32	44
	Completely	8	5	48	13
Modern Vegetation Cover	Bare	20	12	6	2
	Partly	43	64	39	51
	Completely	37	24	54	47

consistency. The scale of the grid cells also determines the scale at which questions can be asked and, therefore, the scale at which landscape change is evaluated. Requantification of vegetation changes in photo-pairs STI 932 and HDL 930b using a larger grid revealed that the overall trends in vegetation change and cover remain largely the same despite minor shifts in categories (Table 4). Larger grid cells result in a lower resolution and thus decrease the percent of "bare" and "completely" covered ground and increase the area of "partly" covered ground. Thus, grid cell size is an important consideration in designing a study of this type.

The best opportunity to resolve the inaccuracies and shortcomings of this technique lies in the integration of this method and those that convert oblique photography to a planar view by georeferencing photographs to a digital elevation model (Aschenwald et al., 2001; Davis et al., 2002; Honda and Nagai, 2002; Corripio, 2004). Although it requires establishment of ground control points in the field, this approach would give spatial attributes to the photo-pairs and allow for the calculation of absolute change in the landscape. As a follow-up to the work described here, the authors successfully experimented with adapting the methodologies developed by Corripio (2004) to repeat photography.

Conclusion

Although the method developed for this project was applied to treeline in GNP, it could be utilized in mapping and measuring numerous other biotic and abiotic landscape changes. Despite its limitations, the quantification process presented in this paper allows for the extraction of considerable information from historical photographs in a medium easily understood by a wide audience and should be of interest to many researchers studying aspects of landscape change.

Acknowledgments

Field work was funded by a Mellon Foundation grant given through the Environmental Studies Program at Middlebury College. The archivists at Glacier National Park, particularly Somer Treat, provided excellent help in locating historical photographs. Blase Reardon assisted with field planning. The U.S. Geological Survey (USGS) Global Change Program and the USGS Glacier Field Station funded additional analysis. Middlebury College and its faculty, notably William Hegman and Dr. Andrea Lloyd, provided space, facilities, and much needed advice to the first author during development of the method and writing of the paper. The authors would also like to thank two anonymous reviewers for their detailed suggestions and comments.

References Cited

Alexander, R. R., Shearer, R. C., and Shepperd, W. D., 1990: Subalpine fir. *In* Burns, R. M., and Honkala, B. H. (eds.), *Silvics of North America*. Forest Service, U.S. Department of Agriculture, Agricultural Handbook 654.

Alftine, K. J., Malanson, G. P., and Fagre, D. B., 2003: Feedback-driven response to multidecadal climatic variability at an alpine treeline. *Physical Geography*, 24: 520–535.

Arno, S. F., 2001: Community types and natural disturbance processes. *In* Tomback, D. F., Arno, S. F., and Keane, R. E. (eds.), *Whitebark pine communities*. Washington, D.C.: Island Press, 74–88.

Aschenwald, J., Leichter, K., Tasser, E., and Tappeiner, U., 2001: Spatio-temporal landscape analysis in mountainous terrain by means of small format photography: a methodological approach. *IEEE Transactions on Geoscience and Remote Sensing*, 39(4): 885–893.

Baars, D. L., Buchanan, R. C., and Charlton, J. R., 1994: *The canyon revisited: a rephotography of the Grand Canyon, 1923/1991*. Salt Lake City: University of Utah Press, 168 pp.

Becwar, M. R., and Burke, M. J., 1982: Winter hardiness limitations and physiography of woody timberline flora. *In* Li, P. H., and Sakai, A. (eds.), *Plant cold hardiness and freezing stress: mechanisms and crop implications*. Vol. 2. New York: Academic Press, 307–323.

Butler, D. R., and DeChano, L. M., 2001: Environmental change in Glacier National Park, Montana: an assessment through repeat photography from fire lookouts. *Physical Geography*, 22: 291–304.

Butler, D. R., Malanson, G. P., and Cairns, D. M., 1994: Stability of alpine treeline in Glacier National Park, Montana, U.S.A. *Phytocoenologia*, 22: 485–500.

Butler, D. R., Malanson, G. P., Bekker, M. F., and Resler, L. M., 2003: Lithologic, structural, and geomorphic controls on ribbon forest patterns in a glaciated mountain environment. *Geomorphology*, 55: 203–217.

Cairns, D. M., 1990: Multi-scale analysis of soil nutrients at alpine treeline in Glacier National Park, Montana. *Physical Geography*, 20: 256–271.

Cairns, D. M., 2001: Patterns of winter desiccation in krummholz forms of *Abies lasiocarpa* at treeline sites in Glacier National Park, Montana, U.S.A. *Geografiska Annaler*, 83A: 157–168.

Cairns, D. M., and Malanson, G. P., 1997: Examination of the carbon balance hypothesis of alpine treeline location in Glacier National Park, Montana. *Physical Geography*, 18: 125–145.

Cairns, D. M., and Malanson, G. P., 1998: Environmental variables influencing the carbon balance at the alpine treeline: a modeling approach. *Journal of Vegetation Science*, 9: 679–692.

Corripio, J. G., 2004: Snow surface albedo estimation using terrestrial photography. *International Journal of Remote Sensing*, 25: 5705–5729.

Davis, T. J., Klinkenberg, B., and Keller, P. C., 2002: Updating inventory using oblique videogrammetry and data fusion. *Journal of Forestry*, 100(3): 45–50.

Easterling, D. R., Karl, T. R., Mason, E. H., Hughes, P. Y., Bowman, D. P., Daniels, R. C., and Boden, T. A. (eds.), 1996: *United States historical climatology network (U.S. HCN) monthly temperature and precipitation data*. Oak Ridge, Tennessee: Carbon Dioxide Information Analysis Center, Oak Ridge National Library.

ESRI (Earth Sciences Research Institute), 2002: GIS and mapping software. Redlands, California.

Fielder, J., Jackson, W. H., and Marston, E., 1999: *Colorado 1870–2000*. Englewood, Colorado: Westcliffe Publishers, 224 pp.

Franklin, J., Moir, W. H., Douglas, G. W., and Wiberg, C., 1971: Invasion of subalpine meadows by trees in the Cascade Range, Washington and Oregon. *Arctic and Alpine Research*, 3: 215–224.

Gruell, G. E., 1983: *Fire and vegetative trends in the Northern Rockies: interpretations from 1871–1982 photographs*. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Harper, A., 1934: Glacial retreat. *The New Zealand Alpine Journal*, 21: 322–326.

Hattenschwiler, S., and Smith, W. K., 1999: Natural seedling occurrence in treeline conifers: a case study from the central Rocky Mountains, USA. *Acta Oecologia*, 20: 219–224.

Hessl, A. E., and Baker, W. L., 1997: Spruce and fir regeneration and climate in the forest-tundra ecotone of Rocky Mountain National Park, Colorado, U.S.A. *Arctic and Alpine Research*, 29: 173–183.

Hofgaard, A., Kullman, L., and Alexandersson, H., 1991: Response of old-growth montane *Picea abies* (L.) karst forest to climatic variability in northern Sweden. *New Phytologist*, 119: 585–594.

Holtmeier, F. K., 2003: *Mountain timberlines ecology, patchiness, and dynamics*. Dordrecht, Netherlands: Kluwer Academic Publishers, 369 pp.

Holtmeier, F. K., and Broll, G., 2005: Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales. *Global Ecology and Biogeography*, 14: 395–410.

Honda, K., and Nagai, M., 2002: Real-time volcano activity mapping using ground-based digital imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*, 57: 144–153.

Kendall, K. C., and Keane, R. E., 2001: Whitebark pine decline: infection, mortality, and population trends. *In* Tomback, D. F., Arno, S. F., and Keane, R. E. (eds.), *Whitebark pine communities: ecology and restoration*. Washington, DC: Island Press, 221–240.

Klasner, F. L., and Fagre, D. B., 2002: A half century of change in alpine treeline patterns at Glacier National Park, Montana, U.S.A. *Arctic and Alpine Research*, 34: 49–56.

Klett, M., 2004: *Third views, second sights: a rephotographic survey of the American West*. Santa Fe, NM: Museum of New Mexico Press, 256 pp.

Klett, M., Manchester, E., Verburg, J., Bushaw, G., and Dingus, R., 1984: *Second View: the Rephotographic Survey Project*. Albuquerque, NM: University of New Mexico Press, 211 pp.

Kullman, L., 1987: Tree-vigor monitoring by repeat photography in the forest alpine tundra ecotone. *Ambio*, 16: 160–162.

Kullman, L., 1991: Pattern and process of present tree-limits in the Tarna region, southern Swedish Lapland. *Fennia*, 169: 25–38.

Kusnierczyk, E. R., and Ettl, G. J., 2002: Growth response of Ponderosa pine (*Pinus ponderosa*) to climate in the eastern Cascades Mountains, Washington, U.S.A. Implications for climate change. *Ecoscience*, 9: 544–551.

Lloyd, A. H., Rupp, S. T., Fastie, C. L., and Starfield, A. M., 2002: Patterns and dynamics of treeline advances on the Seward Peninsula, Alaska. *Journal of Geophysical Research*, 108(D2), 8161, doi:10.1029/2001JD000852.

Malanson, G. P., Brown, D. G., Butler, D. R., Cairns, D. M., Fagre, D. B., and Walsh, S. J., in press: Ecotone dynamics: invasibility of alpine tundra by tree species from the subalpine forest. *In* Butler, D. R., Malanson, G. P., Walsh, S. J., and Fagre, D. B. (eds.), *The changing alpine treeline of Glacier National Park, Montana, USA*. Amsterdam, Netherlands: Elsevier.

Munroe, J. S., 2003: Estimates of Little Ice Age climate inferred through historical rephotography, northern Uinta Mountains, U.S.A. *Arctic, Antarctic, and Alpine Research*, 35(4): 489–498.

Nicholas, R., 2003: Create a grid polygon shapefile (FISHNET) (http://arcscripts.esri.com/details.asp?dbid=128070). Last accessed 2007.

Resler, L. M., 2006: Geomorphic controls of spatial pattern and process at alpine treeline. *The Professional Geographer*, 58(2): 124–138.

Rhemtulla, J. M., Hall, R. J., Higgs, E. S., and Macdonald, S. E., 2002: Eighty years of change: vegetation in the montane ecoregion of Jasper National Park, Alberta, Canada. *Canadian Journal of Forest Research*, 32(11): 2010–2021.

Rochefort, R. A., Little, R. L., Woodward, A., and Peterson, D. L., 1994: Changes in subalpine tree distribution in western North America: a review of climate and other factors. *The Holocene*, 4: 89–100.

Rockwell, D., 2002: *Exploring Glacier National Park*. Guilford, CT: Globe Pequot Press, 336 pp.

Rogers, G. F., 1982: *Then and now—A photographic history of vegetation change in the central Great Basin desert*. Salt Lake City: University of Utah Press, 152 pp.

Rogers, G. F., Malde, H. E., and Turner, R. M., 1984: *Bibliography of repeat photography for evaluating landscape change*. Salt Lake City: University of Utah Press, 179 pp.

Selkowitz, D. J., Fagre, D. B., and Reardon, B. A., 2002: Interannual variations in snowpack in the Crown of the Continent Ecosystem. *Hydrological Processes*, 16: 3651–3665.

Shaw, R. J., and On, D., 1979: *Plants of Waterton-Glacier National Parks and the Northern Rockies*. Missoula, Montana: Mountain Press Publishing Company, 160 pp.

Stevens, G. C., and Fox, J. F., 1991: The causes of treeline. *Annual Revue of Ecological Systems*, 22: 177–191.

Vale, T. R., and Vale, G. R., 1983: *U.S. 40 today: thirty years of landscape change in America*. Madison: University of Wisconsin Press, 198 pp.

Vale, T. R., and Vale, G. R., 1994: *Time and the Tuolumne landscape: continuity and change in the Yosemite high country*. Salt Lake City: University of Utah Press, 212 pp.

Vogler, J. B., 1998: An analysis of vegetation-environment relationships among vegetation communities of anthropogenically disturbed sites, Glacier National Park, Montana. MS thesis. University of North Carolina, Chapel Hill, 235 pp.

Walsh, S. J., and Kelly, N. M., 1990: Treeline migration and terrain variability: integration of remote sensing digital enhancements and digital elevation models. *Proceedings, Applied Geography Conference*, 13: 24–32.

Watson, E., Pederson, G. T., Luckman, B. H., and Fagre, D. B., in press: Glacier mass balance in the northern U.S. and Canadian Rockies: paleo-perspectives and 20th century change. *In* Orlove, B., Wiegandt, E., and Luckman, B. (eds.), *Darkening peaks*. Berkeley, CA: University of California Press.

Webb, R. H., 1996: *Grand Canyon a century of change: rephotography of the 1889–1890 Stanton Expedition*. Tucson, AZ: University of Arizona Press, 290 pp.

Ms accepted October 2006