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Estimates of Little Ice Age Climate Inferred through Historical Rephotography, Northern Uinta Mountains, U.S.A.

Jeffrey S. Munroe

Department of Geology, Middlebury College, Middlebury, VT 05753, U.S.A.
jmunroe@middlebury.edu

Abstract

I replicated and analyzed six photographs taken in A.D. 1870 near the subalpine forest-alpine tundra ecotone in the northern Uinta Mountains to quantify changes in the distribution of vegetation. Three dramatic differences were noted. First, the historical photographs document a treeline 60 to 180 m (mean of ~100 m) lower than at present, with greater depression on west-facing slopes. Given the modern lapse rate for mean July temperature (6.9°C km^{-1}), this difference corresponds to a temperature depression in A.D. 1870 of 0.4 to 1.2°C (mean of 0.7°C). Second, timberline forests in A.D. 1870 were significantly ($P < 0.01$) less dense, with tree densities approximately half those measured in the modern photographs. Third, the area of floodplain meadows decreased ~75% from A.D. 1870 to the present. Because the original photographs were taken within a few decades of the end of the Little Ice Age, ca. A.D. 1850, I assumed that differences in vegetation distribution documented in the repeat photographs represent the biotic response to climate warming over the past ~130 yr. This analysis provides an independent estimate of the magnitude of growing season temperature depression during the Little Ice Age.

Introduction

Repeat photography is a powerful tool for the study of landscape change over time scales from less than 1 yr to more than a century. Photographs provide an objective record of landscape condition during a finite time slice that can be compared with photographs taken from the same position at a later date. Comparison between historical and modern photographs can be made either qualitatively or quantitatively by measuring changes apparent in the pair through photogrammetry. In the western United States, repeat photography, hereafter called "rephotography," has documented invasion of subalpine meadows by trees (Vale, 1987; Vale and Vale, 1994), changes in glacier area and distribution (Veatch, 1969; Post and LaChapelle, 1971; Johnson, 1980), landscape adjustment after wildfire (Gruell, 1983), and changes in the spatial distribution of trees near the subalpine forest-alpine tundra ecotone (Klasner and Fagre, 2002).

The main obstacles to rephotography include (1) uncertainty over the age of the original photograph, (2) the quality of the original photograph, (3) difficulties in locating the original photopoint, and (4) matching the perspective of the original photograph. When the date of an older photograph is unknown, the ability to quantify rates of change of landscape features is compromised because the time interval represented by the photopairs is nonfinite. Historical research can often provide an estimate of the date for otherwise undated photographs, and cultural features in historical photographs can aid in estimating the year of exposure. The quality of the original photograph is unfortunately beyond the control of the researcher. Decaying negatives or prints can be manipulated by image-processing software to alleviate some of the decomposition that obscures features in the original, but the viability of comparisons between historical and modern photographs is limited when the originals are of marginal quality. Location of the original photopoint can be a time-consuming process (Vale and Vale, 1994; Fox, 2001). Familiarity with the region provides the best opportunities for relocating photopoints because recognition of the approximate point from which a historical photograph was taken is dependent on firsthand knowledge of that area. For instance, professional Colorado River guides were involved in relocating the photopoints established by Franklin Nims and Robert Stanton during their 1889–1890 survey of the Grand Canyon (Webb, 1996). Finally, once the original photopoint has been located, an effort must be made to match the perspective in the historical photograph to the greatest extent possible. Accurate photogrammetry is dependent on replication of the original perspective, so quantification of changes in the distribution of vegetation or the evolution of geomorphic features is difficult when lines of sight are not identical.

The current project involved replication of photographs taken in 1870 by William Henry Jackson of the United States Geologic and Geographical Survey of the Territories under the direction of Ferdinand Vandeveer Hayden (Hayden, 1872). The 1870 expedition was the first "Hayden Survey" to include Jackson and his camera, although it is often overshadowed by the longer and better-known 1871 and 1873 expeditions, which returned with images of thermal phenomena in Yellowstone and views of the Colorado Rockies, respectively (Bartlett, 1962). The 1870 Hayden Survey got a late start, departing Fort Carlin on 6 August and traveling generally westward, studying the country north of the Union Pacific railroad, including the North Platte and Sweetwater River drainages, en route to southwestern Wyoming. After reaching Fort Bridger on 12 September, Hayden and his men made three excursions onto the north slope of the Uinta Mountains. In early October the survey moved east into Browns Park along the Green River before heading back to Cheyenne, where they arrived on November 1 (Hayden, 1872; Bartlett, 1962).

The photographs taken by Jackson in the Uintas are a unique source of information about the subalpine landscape. They represent an important collection because they are more than 130 yr old, are remarkably well preserved, and, unlike many other photographs of this vintage, illustrate views at or above treeline. The presence of prominent features in the original photographs allows the photopoints to be relocated. Finally, Jackson's photographs record the condition of the timberline forest near the end of the Little Ice Age, a period of global cooling that ended in other western mountain ranges ca. A.D. 1850 (Carrara and McGimsey, 1981; Porter, 1981; Carrara, 1987; Scuderi, 1987; Schuster et al., 2000). The timing of the historical photographs,

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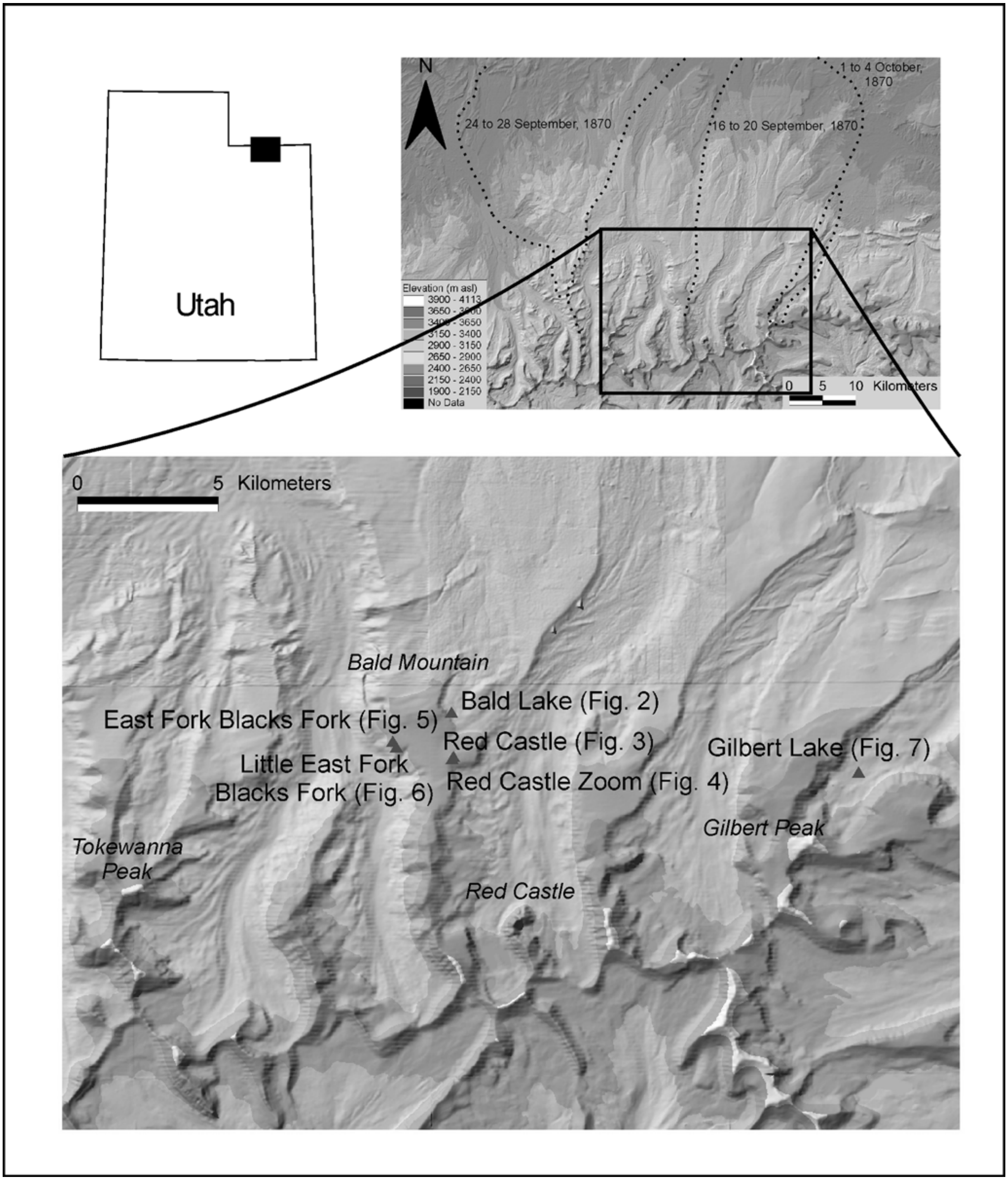

FIGURE 1. Location map of photopoints in the northern Uinta Mountains. The upper map illustrates the routes taken by the Hayden Survey, while the lower map presents the photopoints and the names of prominent topographic features.

therefore, allows the difference between the modern and Little Ice Age climate to be inferred from the contrast in vegetation distribution.

Rephotography has been used before in Utah to study the effects of livestock grazing (Laycock, 1975), to characterize subalpine vegetation (Ellison, 1954), to document changes in riparian vegetation and geomorphology (Shoemaker and Stephens, 1975), to examine the success of stream restoration efforts (Copeland, 1960), and to study the evolution of desert pediments (Hunt, 1973). However, this is the first study to use rephotography to ascertain changes over long periods in timberline forests of northern Utah above the elevation usually affected by wildfire. The main objectives were to (1) replicate as many of the Jackson photographs as possible, (2) quantify the difference in treeline

Table 1

Photopoint locations in the northern Uinta mountains

Negative #	Latitude N	Longitude W	Elevation m	Easting* m	Northing m	Aspect	Figure
057-HS-323	40°51.853″	110°29.442″	3394	542,921	4,523,810	N	2
057-HS-316	40°51.005″	110°29.390″	3508	543,003	4,522,240	SSE	3
057-HS-317	40°50.968″	110°29.432″	3483	542,944	4,522,171	SSE	4
057-HS-319	40°51.326″	110°30.951″	3447	540,806	4,522,822	SW	5
057-HS-318	40°51.305″	110°30.922″	3453	540,847	4,522,784	SSW	6
057-HS-324	40°50.657″	110°19.170″	3330	557,366	4,521,694	SW	7

* UTM Zone 12.

Table 2

Details of the northern Uinta mountain photographs

Figure	Feature	Original date	Rephoto date	f-stop	Speed	Filter
2	Bald Lake	9/19/1870	6/27/2001	f-16	125	none
3	Red Castle (wide)	9/19/1870	6/27/2001	f-11	250	X1 green
4	Red Castle (zoom)	9/19/1870	6/27/2001	f-16	125	X1 green
5	East Fork Blacks Fork	9/19/1870	6/28/2001	f-11/8	125	G15 orange
6	Little East Fork Blacks Fork	9/19/1870	6/28/2001	f-22	160	none
7	Gilbert Peak	10/3/1870	7/1/2001	f-16	160	none

elevation and timberline forest density between the historical and modern photographs, and (3) interpret these changes to yield an estimate of post–Little Ice Age temperature rise.

Physical Setting and Historical Background

The Uinta Mountains are located in northeastern Utah, where they parallel the Utah-Wyoming border for more than 100 km (Fig. 1). The range contains the highest mountains in Utah (>4000 m a.s.l.) and features a rugged landscape of deep glacial canyons alternating with unglaciated uplands. The Uintas are not glacierized today, but more than 940 km^2 of glacier ice was present on the north slope of the range during the Last Glacial Maximum, and smaller cirque glaciers formed, or were rejuvenated, during the Neoglaciation (Munroe, 2001, 2002).

The Hayden Survey reached the north slope of the Uintas on horseback from Fort Bridger, Wyoming, in three separate excursions (Fig. 1) (Hayden, 1872). On 16 September they left Fort Bridger and headed south-southwest up the divide between the Smiths Fork and Blacks Fork drainages. They explored the high upland surface between the glaciated headwaters of these rivers and returned on 20 September. They left again on 24 September and followed the Blacks Fork and the Muddy River toward Elizabeth Mountain, the divide between the Colorado River watershed and the Great Basin. After investigating the complex landscape between the West Fork Blacks Fork and the East Fork of the Bear River, they returned to the lower Bear River valley via Mill Creek and headed overland back to Fort Bridger on 28 September. Finally, on 1 October, the survey departed Fort Bridger, heading southeast to the Henrys Fork, which they followed to the Wyoming-Utah border before leaving the valley and ascending the ridge between the Henrys Fork and the West Fork Beaver Creek. On 3 October they reached the culmination of this ridge, known as Gilbert Peak, the second highest in the Uintas at 4098 m a.s.l. From this summit, Hayden noted: "With such a vast area of country within our range of vision, one could glance back into the abyss of time, and trace, step by step, the origin and slow erosion of these wonderful, gorge-like valleys, one thousand to twelve hundred feet deep, and speculate upon the beginning and growth of this beautiful mountain itself" (Hayden, 1872).

After descending into the West Fork Beaver Creek, the Survey headed downstream to the north, toward the junction with the Henrys Fork, and on to the Green River, ending their brief exploration of the northern Uintas (Hayden, 1872).

Methods

Reprints of the original Hayden Survey photographs were acquired in 8 × 10–inch format from the National Archives and Records Administration in Washington, D.C. (NARA, 2002). The photographs were labeled only with Jackson's original titles, but inspection of topographic maps and Hayden's report to the U.S. Geological Survey (Hayden, 1872), and knowledge of the northern Uintas acquired through previous field seasons, allowed identification of the approximate position of each photopoint prior to the field visit. Once in the field, photopoints were located by comparing prominent skyline features with the view from a given position. Bedded rock outcroppings on distant ridges and the intersection angle of ridges and cols assisted in locating the elevation of the original photopoint, while conspicuous foreground rocks were used to make final adjustments to the camera position. The estimated precision of the photo-point relocations is less than 5 m, and all photo-point locations were recorded with a global positioning system. Ten Jackson photographs record treeline vistas in

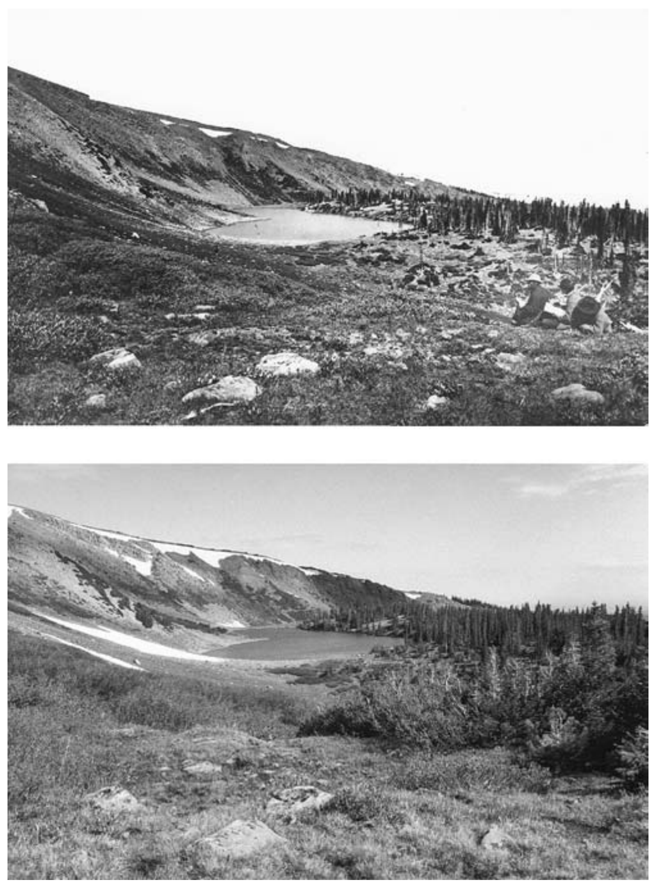

FIGURE 2. Historical and modern photographs of Bald Lake, looking north. The density of trees has increased dramatically on the ridge to the right of the lake (background). In the foreground, a large Pinus contorta *krummholz now occupies the spot where Hayden's men are seated in the historical photograph.*

FIGURE 3. *Historical and modern photographs of the Red Castle taken with a wide-angle lens. An increase in tree density is apparent on the valley floor, while treeline has moved up ~120 m on the far valley wall (left).*

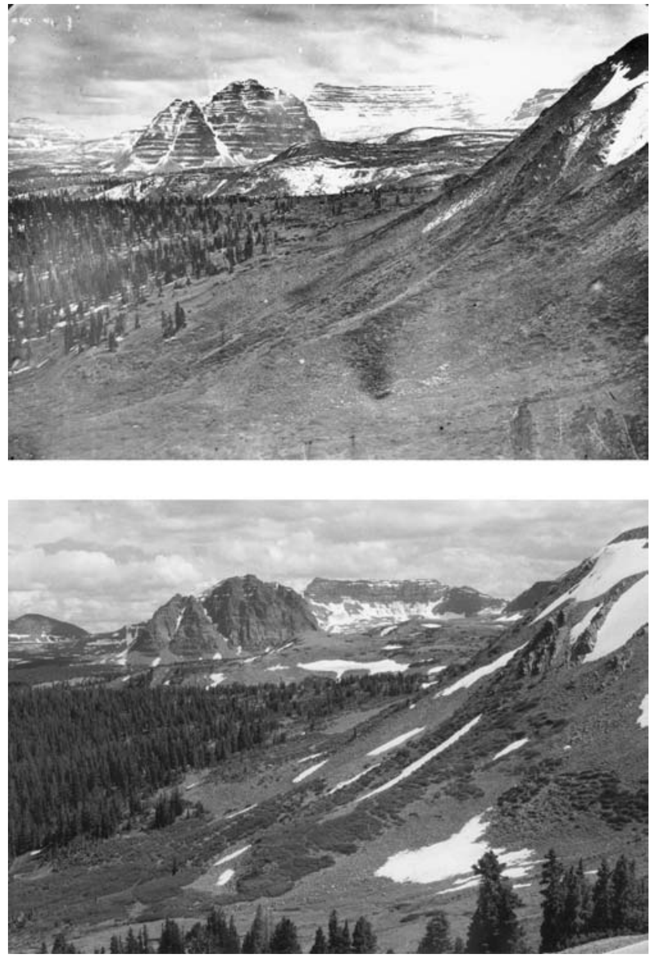

FIGURE 4. *Historical and modern photographs of Red Castle, taken with a zoom lens from a point ~100 m west and slightly below Figure 3. Again, the increase in tree density is obvious on the valley floor, and treeline has risen ~75 m on the far valley wall.*

the northern Uintas, but only 6 of these contain conspicuous skyline features suitable for relocation of the original photopoints.

The modern photographs were taken with a Pentax p130T SLR camera using Kodak T100 black-and-white film (ASA 400). All exposures were taken with a Tiffen Sky 1-A filter, and some used either a Kalt G15 orange filter or a Kalt X1 green filter to best replicate the contrast seen in the original photograph. A total of 18 exposures were taken of each scene (6 with each type of filter) at f-stops ranging from f-22 to f-8 and shutter speeds from 1/1000 s to 1/30 s. The photographs were not replicated at the same time of year as the originals; however, care was taken to minimize effects of shadows on the landscape in each scene, which can be critical to interpretations of change. The positions of the minor snowbanks and the phenology of the dominantly coniferous vegetation did not present obstacles to the comparison of the photographs.

All negatives were developed by a commercial lab, and the best repeat photograph of each scene, in terms of contrast, balance, area covered by shadows, etc., was printed in an 8 × 10–inch format to match the historical photographs. The photographs were then scanned at 1000 dpi on a flatbed scanner. The original and repeat version of each scanned image were arranged in Corel Draw, and the original photograph taken by Jackson's wide-angle camera was cropped slightly to match the narrower width of field captured in the modern exposure.

For 5 of the photopairs, the elevation of treeline was determined by comparison with obvious topographic features, including benches, cols, and minor summits, which could be identified on both the historical and modern photographs and on 7.5-in topographic maps. Each of the 5 photopairs included one prominent slope on which measurements could be made (aspect noted in Table 3), and the highest elevation of trees was noted on each of these slopes. Sources of error in these calculations include the imprecision in identifying the more subtle topographic features, the slightly blurred nature of the original photographs, and the 12-m (40-ft) contour interval of the maps. Furthermore, the error varies with the distance between the photopoint and the point of measurement but is likely ±12 m for foreground measurements and up to ±24 m for measurements made on distant slopes.

The density of timberline forests in 3 of the photopairs was calculated by two different methods. Where the timberline was located far from the camera, a grid of intersecting lines was randomly placed over an area of trees, and the number of grid squares containing trees or tree clumps was counted. Where individual trees could be clearly distinguished, either because the trees were larger or closer to the observer, the number of trees directly overlain by gridline intersections was counted. This process was repeated ten times with both the historical and modern photographs ($n = 20$ for each photopair), and the mean value for each photograph was calculated. The same grid was used for each pair of photographs, although each placement of the grid was random. Differences

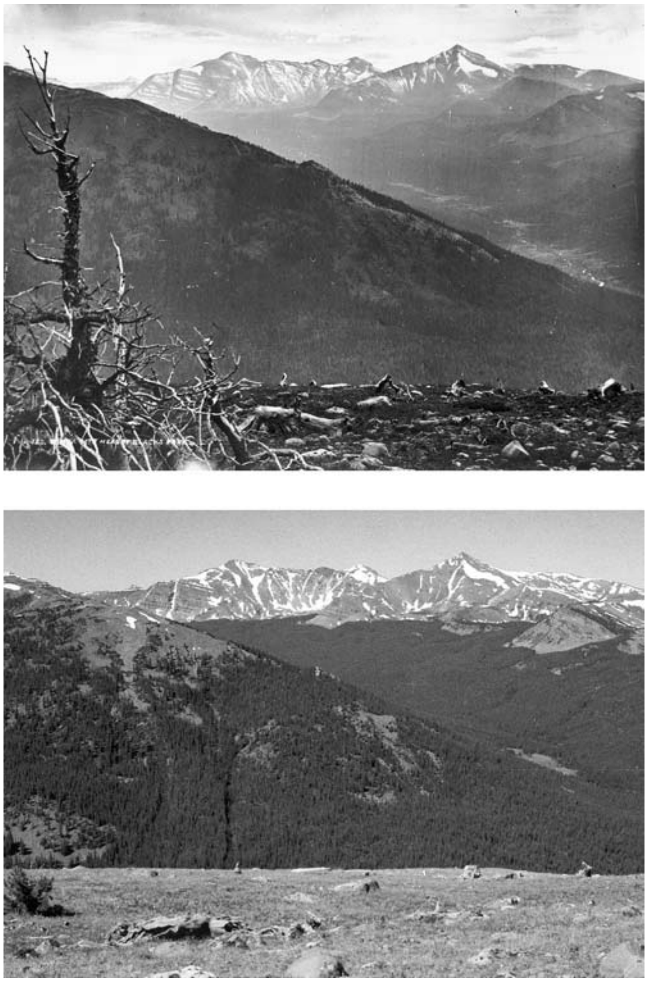

FIGURE 5. Historical and modern photographs of the East Fork Blacks Fork. The modern photograph was taken from a point ~10 m in front of the historical photograph because the apparently dead krummholz on the A.D. 1870 scene has been rejuvenated and blocks the view from the original photopoint completely. The area of valley-floor meadows has decreased 76% percent in 130 yr, while tree density has nearly doubled on the midground slope and treeline has risen ~90 m. The prominent snowbank on the north ridge of Tokewanna Peak appears unchanged.

FIGURE 6. Historical and modern photographs of the Little East Fork Blacks Fork. The area of valley-floor meadows has decreased 71% since 1870, while treeline on the west-facing valley wall (left side) has risen 183 m. A grove of dense Pinus contorta *seedlings has filled in much of the left midground. The prominent standing snag in the center of the historical photograph was still standing in 2001.*

between the counts for each of the two photographs were compared using a Mann-Whitney U-test.

Cropped and zoomed bitmaps of the 2 photopairs illustrating changes in the distribution of meadows on the valley floor were imported into ArcView. A polygon outlining each meadow was then digitized on-screen, and the resulting areas were tabulated to yield a total meadow area for the historical and modern photograph. These values are not true planimetric areas because of the distortion inherent in the oblique landscape perspective. However, given that the original photopoints were relocated as precisely as possible, comparison between the photographs is valid for a measure of relative change.

Finally, modern lapse rates for mean annual, mean summer (June/July/August), and mean July temperature in the northern Uintas were determined from temperatures measured at Manilla, Utah (1939 m a.s.l.); Evanston, Wyoming (2076 m a.s.l.); four Snowpack Telemetry (SNOTEL) stations in the northern Uintas (ranging from 2758 to 3078 m a.s.l.); and a Remote Automated Weather Station (RAWS) located at 3967 m a.s.l. on the Uinta ridge crest.

Results

REPLICATION

Six photographs taken by Jackson in the northern Uintas were replicated (Fig. 1). Table 1 presents the location data for each of the photopoints, and Table 2 presents information about the original and modern photographs. Jackson's photograph titled "Carter's Lake" was taken on the south side of Bald Lake, looking northward (Fig. 2). Jackson took 2 separate exposures of the Red Castle, which the Survey called "Hayden's Cathedral," at the head of the East Fork Smiths Fork (Hayden, 1872). One was taken with a wide-angle lens from a point above the switchbacks on Forest Service Trail 111 (Fig. 3), and the other was taken from a point ~100 m west at a slightly lower elevation with a zoom lens (Fig. 4). Both photographs of the Blacks Fork drainage were taken ~2 km to the west from the Red Castle photographs. Figure 5 shows the historical and modern photographs of the East Fork Blacks Fork. Tokewanna Peak (4014 m a.s.l.), featuring a sinuous cornice on its northern (right) ridgeline, is conspicuous. Figure 6 shows a view due south from a point 250 m southeast of Figure 5, looking straight up the Little East Fork Blacks Fork valley. Finally, Figure 7 shows the view of Gilbert Peak over Lake Gilbert, which Hayden named "Lake Annie." The Survey descended the

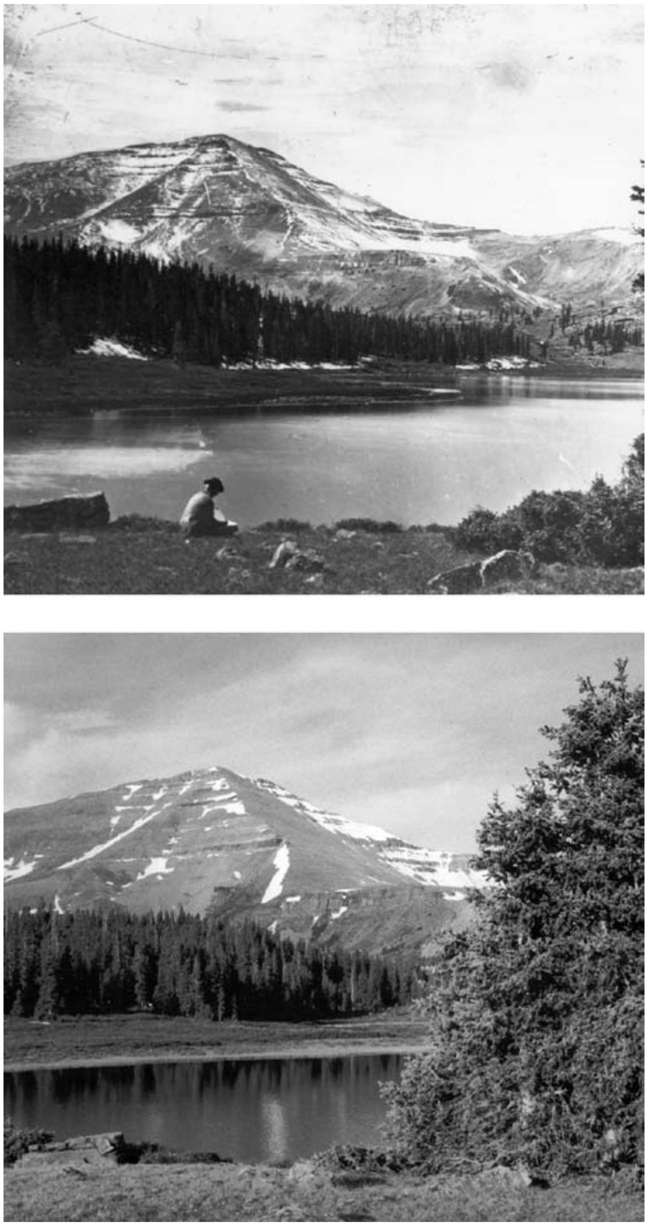

FIGURE 7. Historical and modern photographs of Gilbert Peak with Gilbert Lake in the foreground. Treeline has risen ~60 m on the headwall below Gilbert Peak, while the tree clump on the right has increased greatly in size, partially obstructing the view.

headwall in the background "with great difficulty" after summitting the peak on 3 October 1870 (Hayden, 1872).

COMPARISONS

I noted three dramatic differences between the historical and modern photographs. First, 5 of the historical photographs document a treeline 60 to 180 m (mean of ~100 m) lower than at present (Table 3); treeline quantification was not possible on the Bald Lake photograph (Fig. 2). Treeline is considered to be the uppermost elevation of upright trees (Little, 1979). A change in treeline elevation is particularly apparent in Figures 3, 4, and 6. Treeline depression on west-facing slopes (Figures 3 and 6, mean of 152 m) was approximately twice that on slopes with northeast aspects (Figures 4, 5, and 7, mean of 76 m).

Table 3

Treeline calculations

		Fig. 3*		Fig. 4		Fig. 5		Fig. 6		Fig. 7	
	Units	1	2	1	2	1	2	1	2	1	2
Treeline	m	3232	3354	3354	3430	3293	3384	3171	3354	3354	3415
Aspect**		West		North		Northeast		West		Northeast	
Change	m	122		76		91		183		61	
July temp change***	°C	0.79		0.50		0.59		1.19		0.40	
Modern treeline	°C	9.8		9.3		9.6		9.8		9.4	
Mean Temp Change	°C	0.69									
Mean Treeline Change	m	107									

* 1 is historic photograph, 2 is modern.

** Aspect of the slope treeline was measured on, not aspect of the photograph.

*** From modern July lapse rate of 6.9°C Km^{-1}.

Second, the timberline forest was considerably less dense in A.D. 1870. Three of the photopairs provide detailed views of the timberline forest (Figs. 2, 4, and 5). In these photopairs, mean tree densities in the historical photographs are approximately half those measured in the modern photographs (Table 4), a difference that is highly significant ($P < 0.01$).

Finally, two photopairs (Figs. 5 and 6) record the distribution of trees and meadows on valley bottoms. Comparison of the historical and modern photographs reveals that the area of floodplain meadows in the East Fork (Fig. 5) and Little East Fork Blacks Fork (Fig. 6) decreased by ~75% over the past 130 yr.

LAPSE RATES

Lapse rates in mountainous areas are affected by numerous variables, including complex topography, snow cover, and air-mass humidity (Barry, 1992). This analysis attempted to limit potential error by employing multiple ($n = 7$) data points distributed over a wide elevation range (~1.8 km) solely on the north slope of the mountains. Atmospheric lapse rates for mean annual, mean summer, and mean July temperatures in the northern Uintas based on modern data (Table 5) are shown in Figure 8. Mean temperature values are highly correlated with elevation, and the resulting lapse rates are close to the saturated adiabatic lapse rate of 6°C km^{-1} (Linacre and Geerts, 1997). The summer (and July) gradients are steeper than the annual gradient, reflecting the dry summer climate of the northern Uintas. For comparison, lapse rates for mean summer temperature ranging from 6.5 to 8.4°C km^{-1} were calculated for the Colorado Rockies (Leonard, 1989).

Discussion

PALEOCLIMATE INTERPRETATIONS

Comparison of the modern and historical photographs reveals that treeline was lower in the northern Uintas at the close of the Little Ice Age. Similar results have been noted for the La Plata Mountains of southern Colorado (Petersen, 1988), and the Sierra Nevada (Klikoff, 1965). The elevation of treeline is strongly correlated with mean growing season temperature (Troll, 1973; Tranquillini, 1979). Therefore, past changes in treeline can be interpreted as proxy evidence for temperature fluctuations (Fall, 1997; Munroe, 2003). Given the modern July lapse rate of 6.9°C km^{-1}, the measured treeline rise since A.D. 1870 corresponds to an increase in mean July temperature of 0.4 to

Table 4

*Tree density measurements**

	Bald Lake (Fig. 2)		Red Castle zoom (Fig. 4)		East Fork Blacks Fork (Fig. 5)	
	Original	*Rephoto*	*Original*	*Rephoto*	*Original*	*Rephoto*
Mean	23.3	54.8	123.7	138.6	41.1	76.3
St dev	3.9	3.3	3.0	1.5	4.7	3.7
	Mann-Whitney		Mann-Whitney		Mann-Whitney	
	Ua	100	Ua	100	Ua	100
	z	−3.74	*z*	−3.74	*z*	−3.74
	P	0.0001	*P*	0.0001	*P*	0.0001

* Means are comparable within photopairs, but not between pairs.

Table 5

Data used for determining the north slope lapse rates

Station name	Elevation (m)	July °C	Summer °C	Annual °C
Chepeta RAWS	3697	9.0	6.6	−2.6
Steel Creek Park SNOTEL	3078	9.9	9.0	−0.6
Trout Creek SNOTEL	2848	12.1	10.7	0.5
Hole in the Rock SNOTEL	2796	14.2		
Hickerson Park SNOTEL	2758	13.3	11.9	1.8
Evanston, Wyoming	2076	17.4	15.6	4.3
Manilla, Utah	1939	20.5	18.8	7.4
Gradient °C km^{-1}	—	6.5	6.7	5.3
0°C Isotherm (m)	—	4862	4526	3079

1.2°C, with a mean of 0.7°C (Fig. 8). Therefore, the lower treeline and reduced timberline forest density documented in the historical photographs reflect a depression of mean July temperatures ~0.7°C at the end of the Little Ice Age. For comparison, the mean northern hemisphere temperature rise since the mid-1800s is estimated at 0.9°C (National Assessment Synthesis Team, 2001), and a depression of summer temperature of 0.2°C during the Little Ice Age was calculated for the Wind River Range, ~250 km north of the Uintas, on the basis of glacier equilibrium-line altitudes (Zielinski and Davis, 1989). A much larger post–Little Ice Age temperature change of ~5°C was calculated for the Wind Rivers from oxygen isotopes in an ice core using a transfer function derived from modern snowpack data, although the magnitude of this change may have been overestimated because changes in storm tracks also affect $\delta^{18}O$ values (Naftz et al., 2002).

The second contrast revealed by the rephotography is the increase in tree density within the timberline forest. One possible explanation for the change is that the historical photographs document a timberline forest out of equilibrium with climate, perhaps due to insect infestation or wildfire. A major outbreak of spruce-bark beetle was reported in the upper subalpine forests of the White River Plateau in northwestern Colorado (~200 km to the east) in the 1870s (Sudworth, 1900; Feiler et al., 1997). Yet the disturbance pattern is not suggestive of an insect infestation (Steve Munson, personal communication, 29 January 2002), no evidence of forest fire is seen, and the photopoints are distributed across more than 200 km^2. Furthermore, similar increases in tree density over the past century have been noted for timberline forests in the Sierra Nevada (Vankat and Major, 1978; Vale, 1987), and Glacier National Park (Butler et al., 1994; Klasner and Fagre, 2002), making it more likely that the low tree density in the Uintas ca. A.D. 1870 reflects a regional climatic condition.

The magnitude of the change revealed by the photographic comparisons, therefore, indicates a major increase in the productivity or habitability of the upper subalpine environment over the past 130 yr. *Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* (subalpine fir), the main components of the timberline forest in the Uintas, grow in the coolest high-elevation forests of the western United States (Burns and Honkala, 1990). Both species prosper in mean July temperatures from 10 to 13°C and endure winter snowfall in excess of 400 cm (Burns and Honkala, 1990). In the upper subalpine environment of the northern Uintas, the mean July temperature ranges from 9.3 to 9.8°C at treeline (Table 3) and from 10 to 11°C at timberline, the uppermost elevation of continuous forest (Wardle, 1965), given the regression fit to the data in Figure 8. Frost can occur any month of the year at elevations where *Picea engelmannii* and *Abies lasiocarpa* are common, although they require 30 to 60 frost-free days per year. Yet seedlings of both species are vulnerable to frost at certain times; newly germinated *Picea engelmannii* seedlings are particularly affected by fall frosts, while year-old seedlings of both species are susceptible to freezing temperatures early in the growing season, when the water content of tissues is high (Burns and Honkala, 1990). Although the tree density in the timberline forest was low when the historical photographs were taken, living mature trees were present among the standing snags and downed timber. Therefore, it seems likely that an increase in the frequency of late spring and early fall frosts had a negative impact on seedling germination during the Little Ice Age. Particularly robust trees, or those that were youthful at the onset of the Little Ice Age, may have survived while the climate cooled and treeline descended. But as older trees expired, a decrease in frost-free days limited seedling recruitment, resulting in an overall decrease in timberline forest density.

The third major difference revealed by comparison of the historical and modern photographs is the significant decrease in area of valley-floor meadows along the East Fork and Little East Fork Blacks Fork (Figs. 5 and 6). This change reflects the migration of *Pinus contorta* (lodgepole pine) onto river floodplains formerly dominated by sedges, forbs, and graminoids. Invasion of meadows by trees has been also been noted in studies of the Yosemite region (Vale, 1987), the Wind River Range (Dunwiddie, 1977) and Medicine Bow Mountains of Wyoming (Vale, 1978), Yellowstone National Park (Jakubos and Romme, 1993), the Cascades (Franklin et al., 1971), and the Olympic Mountains (Fonda and Bliss, 1969). Numerous mechanisms have been promoted for explaining the shift in the forest-meadow ecotone, including livestock grazing (Dunwiddie, 1977), fire suppression (Vale, 1987), changes in soil moisture status (Jakubos and Romme, 1993), and climate warming (Franklin et al., 1971; Rochefort et al., 1994). Of these mechanisms, fire suppression and livestock grazing seem inadequate to explain the magnitude of the decrease in meadow area given the minor grazing pressure and the lack of evidence for widespread fires in the *Pinus contorta* forests that cloak the valley bottom. Soil moisture content may have been greater during the cooler Little Ice Age, but valley-floor meadows in the Uintas are underlain by extremely permeable gravel, making it unlikely that tree seedlings were formerly excluded from the meadows by a high water table. Thus, climate warming seems to be the most viable explanation. Temperature data collected elsewhere in the Uintas indicate that a severe microclimate, including frequent summer frosts, makes subalpine meadows inhospitable to tree seedlings (Munroe, unpublished data). Therefore, it is reasonable to conclude that the migration of *Pinus contorta* into the valley-floor meadows has been driven by the same climate warming that produced the higher treeline and denser timberline forests.

An alternative, but related, possibility is that the reduction in meadow area reflects the effects of large, possibly nival, flood events

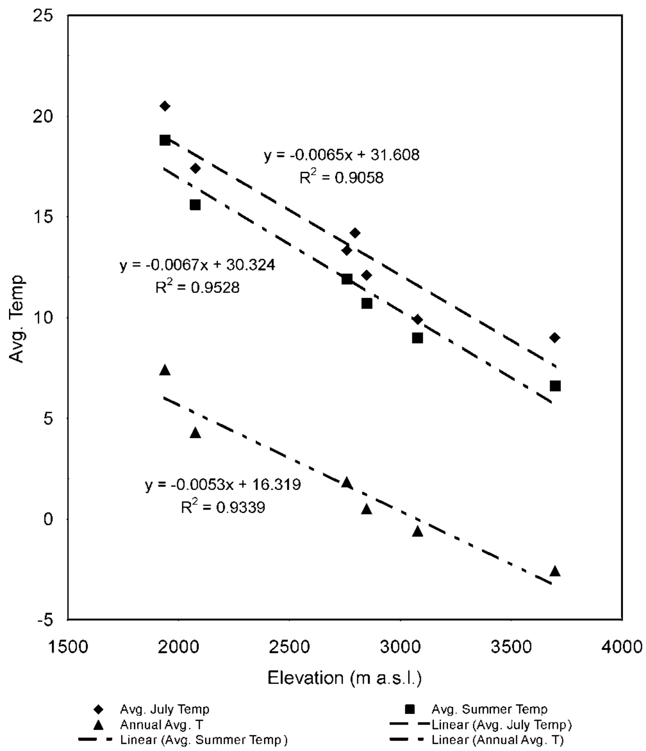

FIGURE 8. Atmospheric lapse rates for mean annual, mean summer (June/July/August), and mean July temperatures in the northern Uintas, determined from the data in Table 5.

near the end of the Little Ice Age that scoured loamy soils from floodplains and deposited coarser overbank gravels more favorable to colonization by conifer seedlings. This mechanism has been proposed for northeastern Yellowstone National Park, where tree rings provide evidence for erosive flood events that led to abandonment of a river terrace after A.D. 1790, coincident with early warming out of the Little Ice Age (Meyer, 2001). Profiles from floodplain soils in the Uintas that could test this theory are lacking, but future research will attempt to evaluate this possibility.

Other Evidence

Other evidence bearing on the Little Ice Age climate in the northern Uintas is provided by subfossil wood present above modern treeline on Bald Mountain (Fig. 1). Similar wood from elsewhere in the Rocky Mountains has been taken as evidence of higher treeline during the early Holocene climatic optimum, or "altithermal" (Carrara et al., 1991). Downed logs, in situ stumps, and upright delimbed boles on the north side of Bald Mountain indicate a treeline up to 60 m higher than the modern level. Given the modern lapse rate (Fig. 8), this rise in treeline corresponds to an increase of mean July temperature of 0.4°C.

Many of the stumps have been severely abraded by windblown ice, giving the impression of considerable antiquity. A sample cut from one of these stumps was radiocarbon dated (Beta-146448) to 310 ± 50 ^{14}C yr B.P., which calibrates to A.D. 1480 to 1663 (at 2σ). Therefore, treeline was at least 60 m higher ~A.D. 1550. Because the dated sample was from the outer part of the stump, the radiocarbon age limits the time of death of the tree. Thus, while a ring count was not possible due to the weathered nature of the stump, the actual germination of the tree may have occurred a century or more before A.D. 1550.

A higher treeline in the northern Uintas shortly before A.D. 1550 is consistent with contemporaneous evidence for warmer-than-modern climates in the southwestern United States (Dean, 1994; Petersen, 1994; Meyer et al., 1995; Pederson, 2000). Globally distributed indicators of a warmer climate at this time have been considered evidence of a "Medieval Warm Period," although the term was defined on the basis of historical records of warmer-than-modern conditions in Europe from A.D. 850 to A.D. 1250 (Lamb, 1965). In the Uintas, the Medieval Warm Period is marked by an increase in the charcoal content of sediment in Lily Lake, ~30 km west of the replicated photographs. Fires were essentially absent from Lily Lake between 1050 B.C. and A.D. 450, but medium-intensity fires, with a recurrence interval of approximately 200 yr, were common from A.D. 450 to the end of the studied record at A.D. 1100 (Munroe and Laidlaw, 2002). Taken together, the regional and local evidence suggests that slightly warmer conditions prevailed in the Uintas in the centuries prior to A.D. ~1550. The subfossil wood above modern treeline on Bald Mountain, therefore, represents the slowly decaying remains of trees that germinated during this warm interval and were subsequently extirpated by the colder Little Ice Age climate.

Conclusion

Replication of photographs taken in A.D. 1870 reveals significant changes in treeline elevation, timberline forest density, and the area of valley-floor meadows in the northern Uinta Mountains. Sparse timberline forests, lower absolute treeline elevations, and more expansive valley-floor meadows are taken as evidence of a cooler climate during the Little Ice Age, which ended ca. A.D. 1850. In the 131 yr after the original photographs were taken, the maximum elevation attained by trees rose ~100 m, the density of trees in timberline forests doubled, and *Pinus contorta* trees encroached on valley-floor meadows. These changes correspond to a rise in mean July temperature of ~0.7°C, a decrease in the frequency of early fall and late spring frosts, and a general amelioration of open-meadow microclimates corresponding to warmer post–Little Ice Age conditions.

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References Cited

Barry, R. G., 1992: *Mountain Weather and Climate.* New York: Routledge. 402 pp.

Bartlett, R. A., 1962: *Great Surveys of the American West.* Norman: University of Oklahoma Press. 408 pp.

Burns, R. M., and Honkala, B. H., 1990: *Silvics of North America: 1. Conifers; 2. Hardwoods.* Washington, DC: U.S. Department of Agriculture, Forest Service.

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

Carrara, P. E., 1987: Holocene and latest Pleistocene glacial chronology, Glacier National Park, Montana. *Canadian Journal of Earth Science,* 24: 387–395.

Carrara, P. E., and McGimsey, R. G., 1981: The late-Neoglacial histories of the Agassiz and Jackson glaciers, Glacier National Park, Montana. *Arctic and Alpine Research,* 13: 183–196.

Carrara, P. E., Trimble, D. A., Rubin, M., 1991: Holocene treeline fluctuations in the northern San Juan Mountains, Colorado, U.S.A., as indicated by radiocarbon-dated conifer wood. *Arctic and Alpine Research,* 23: 233–246.

Copeland, O. L., 1960: Watershed restoration: a photo-record of conservation practices applied in the Wasatch Mountains of Utah. *Journal of Soil and Water Conservation,* 15: 105–120.

Dean, J. S., 1994: The Medieval Warm Period on the southern Colorado Plateau. *Climatic Change,* 26: 225–241.

Dunwiddie, P. W., 1977: Recent tree invasion of subalpine meadows in the Wind River Mountains, Wyoming. *Arctic and Alpine Research,* 9: 393–399.

Ellison, L., 1954: Establishment of vegetation on depleted subalpine range as influenced by microenvironment. *Ecological Monographs,* 24: 89–184.

Fall, P. L., 1997: Timberline fluctuations and late Quaternary paleoclimates in the Southern Rocky Mountains, Colorado. *Geological Society of America Bulletin,* 109: 1306–1320.

Feiler, E. J., Anderson, R. S., and Koehler, P. A., 1997: Late Quaternary paleoenvironments of the White River Plateau, Colorado, U.S.A. *Arctic and Alpine Research,* 29: 53–62.

Fonda, R. W., Bliss, L. C., 1969: Forest vegetation of the montane and subalpine zones, Olympic Mountains, Washington. *Ecological Monographs,* 39: 271–301.

Fox, W. L., 2001: *View Finder: Mark Klett, Photography, and the Reinvention of Landscape.* Albuquerque: University of New Mexico Press. 309 pp.

Franklin, J. F., and Moir, W. H., Douglas, G. W., 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, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station.

Hayden, F. V., 1872: *Preliminary Report of the United States Geological Survey of Wyoming and Portions of Contiguous Territories.* Washington, DC: Government Printing Office. 511 pp.

Hunt, C. B., 1973: Thirty-year photographic record of a shale pediment, Henry Mountains, Utah. *Geological Society of America Bulletin,* 84: 689–695.

Jakubos, B., Romme, W. H., 1993: Invasion of subalpine meadows by lodgepole pine in Yellowstone National Park, Wyoming, U.S.A. *Arctic and Alpine Research,* 25: 382–390.

Johnson, A., 1980: *Grinnell and Sperry Glaciers, Glacier National Park, Montana: A Record of Vanishing Ice.* U.S. Geological Survey Professional Paper 1480.

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

Klikoff, L. G., 1965: Microenvironmental influence on vegetational pattern near timberline in the central Sierra Nevada. *Ecological Monographs,* 35: 187–211.

Lamb, H. H., 1965: The early medieval warm epoch and its sequel. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 1: 13–37.

Laycock, W. A., 1975: *Rangeland Reference Areas.* Denver: Society for Range Management. 66 pp.

Leonard, E. M., 1989: Climatic change in the Colorado Rocky Mountains: estimates based on modern climate at late Pleistocene equilibrium lines. *Arctic and Alpine Research,* 21: 245–255.

Linacre, E., and Geerts, B., 1997: *Climates and weather explained.* London: Routledge. 432 pp.

Little, E. L. J., 1979: *Checklist of United States Trees (Native and Naturalized).* Washington, DC: U.S. Department of Agriculture.

Meyer, G. A., 2001: Recent large-magnitude floods and their impact on valley-floor environments of northeastern Yellowstone. *Geomorphology,* 40: 271–290.

Meyer, G. A., and Wells, S. G., Jull, A. J. T., 1995: Fire and alluvial chronology in Yellowstone National Park: climatic and intrinsic controls on Holocene geomorphic processes. *Geological Society of America Bulletin,* 107: 1211–1230.

Munroe, J. S., 2001: Late Quaternary history of the northern Uinta Mountains, northeastern Utah. Ph.D. dissertation, University of Wisconsin, Madison, Wisconsin. 398 pp.

Munroe, J. S., 2002: Timing of post-glacial cirque reoccupation in the northern Uinta Mountains, northeastern Utah, U.S.A. *Arctic, Antarctic, and Alpine Research,* 34: 38–48.

Munroe, J. S., 2003: Holocene timberline and paleoclimate of the northern Uinta Mountains, northeastern Utah, U.S.A. *The Holocene,* 13: 175–185.

Munroe, J. S., Laidlaw, J. S., 2002: A 5000-year record of fire and sedimentary response for the northwestern Uinta Mountains, U.S.A. *Abstracts with Programs,* 34.

Naftz, D. L., Suson, D. D., Schuster, P. F., Cecil, L. D., and Dettinger, M. D., Michel, R. L., Kendall, C., 2002: Ice core evidence of rapid air temperature increases since 1960 in alpine areas of the Wind River Range, Wyoming, United States. *Journal of Geophysical Research,* 107: 3.1–3.16.

NARA, 2002: U.S. National Archives and Records Administration. http://www.archives.gov/index.html

National Assessment Synthesis Team, 2001: *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change.* Cambridge: Cambridge University Press. 620 pp.

Pederson, J. L., 2000: Holocene paleolakes of Lake Canyon, Colorado Plateau: paleoclimate and landscape response from sedimentology and allostratigraphy. *Geological Society of America Bulletin,* 112: 147–158.

Petersen, K. L., 1988: Climate and the Dolores River Anasazi: a paleoenvironmental reconstruction from a 10,000 year pollen record, La Plata Mountains, southwestern Colorado. *University of Utah Anthropological Papers*: 152.

Petersen, K. L., 1994: A warm and wet Little Climatic Optimum and a cold and dry Little Ice Age in the southern Rocky Mountains, U.S.A. *Climatic Change,* 26: 243–269.

Porter, S. C., 1981: Glaciological evidence of Holocene climate change. *In* Wigley, T. M. L., Ingrahm, M. J., and Farmer, G. (eds.), *Climate and History.* Cambridge: Cambridge University Press, 82–110.

Post, A. S., LaChapelle, E. R., 1971: *Glacier Ice.* Seattle: University of Washington Press. 111 pp.

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

Schuster, P. F., White, D. E., and Naftz, D. L., Cecil, L. D., 2000: Chronological refinement of an ice core record at Upper Fremont Glacier in south central north America. *Journal of Geophysical Research,* 105: 4657–4666.

Scuderi, L. A., 1987: Late-Holocene upper timberline variation in the southern Sierra Nevada. *Nature,* 325: 242–244.

Shoemaker, E. M., Stephens, H. G., 1975: First photographs of the Canyon Lands. *In* Fasset, J. E. (ed.), *Canyonlands Country.* Four Corners Geological Society, 111–222.

Sudworth, G. B., 1900: White River timberland reserve. *Twentieth Annual Report, 1989–1899, Part V, U.S. Geological Survey.* U.S. Geological Survey.

Tranquillini, W., 1979: *Physiological Ecology of the Alpine Timberline: Tree Existence at High Altitudes with Special Reference to the European Alps.* Berlin: Springer-Verlag. 137 pp.

Troll, C., 1973: The upper timberlines in different climatic zones. *Arctic and Alpine Research,* 5: A3–A18.

Vale, T. R., 1978: Tree invasion of Cinnabar Park in Wyoming. *American Midland Naturalist,* 100: 277–284.

Vale, T. R., 1987: Vegetation change and park purposes in the high elevations of Yosemite National Park, California. *Annals of the Association of American Geographers,* 77: 1–18.

Vale, T. R., Vale, G. R., 1994: *Time and the Tuolumne Landscape.* Salt Lake City: University of Utah Press. 212 pp.

Vankat, J., Major, J., 1978: Vegetation changes in Sequoia National Park, California. *Journal of Biogeography,* 5: 377–402.

Veatch, F. M., 1969: *Analysis of a 24-Year Photographic Record of Nisqually Glacier, Mount Rainier National Park, Washington.* U.S. Geological Survey Professional Paper 631.

Wardle, P., 1965: A comparison of alpine timberlines in New Zealand and North America. *New Zealand Journal of Botany,* 3: 113–135.
Webb, R. H., 1996: *Grand Canyon: A Century of Change.* Tucson: University of Arizona Press. 290 pp.
Zielinski, G. A., and Davis, P. T., 1989: Inferred climatic conditions based on equilibrium-line altitudes of former glaciers at type localities in the Wyoming Wind River Range and Colorado Front Range. *Abstracts with Programs,* 21: 211.

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