VEGETATION CHANGE TRENDS IN YOSEMITE NATIONAL PARK OVER THE LAST CENTURY (1897-2008)

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By

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San Francisco, California

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CERTIFICATION OF APPROVAL

I certify that I have read *VEGETATION CHANGE TRENDS IN YOSEMITE NATIONAL PARK OVER THE LAST CENTURY (1897-2008)* by Noah S. Wasserman, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requests for the degree: Master of Arts in Geography: Resource Management & Environmental Planning at San Francisco State University.

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At the highest elevations, the multi-decadal life cycles of tree species require monitoring techniques that are able to cover these extended timelines. In order to expand the temporal scale of change detection, repeat-photography research methods are applied to alpine and sub-alpine vegetation ecosystems in and around Yosemite National Park, California. Historic photographs provide the backdrop for a qualitative assessment of vegetation in sub-alpine and alpine vegetation zones. Over 80 photographs from circa-1900 and circa-1985 were compared to those taken in 2008 to add an additional quarter century to previous change detection studies completed in the region. Growth trends as documented included 1) increased density of Krummholz stands, 2) increased density of sub-alpine forest stands at the tree line, 3) invasion of individual trees into meadows, 4) reduced instances of forest clearings and increased forest density, and 5) growth of trees on domes and rocky slopes. Evidence of upslope movement of the tree line was visible, confirming current knowledge of tree line systems in the American West, but contrary to previous studies conducted in this specific area. The application of GPS and other technological innovations allow for continued monitoring of upper elevation systems and follow-up is strongly encouraged.

Keywords: Vegetation change, repeat photography, national parks, Yosemite National Park, Sierra Nevada Mountains.

I certify that the Abstract is a correct representation of the content of this thesis.

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Barbara A. Holzman, Ph.D Date

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A heart-felt 'thank you' goes to the National Park Service, for their continued protection of our soaring natural cathedrals. I hope this thesis improves understanding and insight for future management of the Tuolumne area.

This project is dedicated to my family, who introduced me to the Sierra Nevada, and whose foot steps I will always follow along mountain trails. Lastly, my work here would not have been possible without the loving encouragement of my wife, Jessica, who jealously watched my dusty pack and eastward bound tail lights disappear before too many summer sunrises.

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INTRODUCTION

In order to advance our understanding of montane vegetation dynamics in the American West, we must refine the tools we utilize to identify ecosystem changes over time. At the highest elevations, the multi-decadal life cycles of tree species require monitoring techniques that are able to resolve these extended time scales of change. Decadal scale observations help to detect vegetation growth trends and when applied, forest management policy can thus reflect a greater understanding of the changing nature of their managed resources. In particular, photography has become an increasingly reliable and important tool used to identify change across decades.

To fill a gap in long term evaluation of change at higher elevations in the central Sierra Nevada, this study uses repeat-photography analysis to identify vegetation change trends over the last century (1897-2008). Historic photographs, concentrated in the high country of the Sierra Nevada Mountain Range in Yosemite National Park, California, USA and the surrounding area, provide visible benchmarks for a qualitative assessment of arboreal growth in sub-alpine and alpine vegetation zones. These data expand vegetation change analysis and provide a digital baseline for future repeat-photography study of growth trends.

In California, close to 50 percent of the state's 7,000 vascular plant species occur in the Sierra Nevada Mountain Range, more than one-ninth of these are endemic, and 200 are considered rare (SNEP 1996). In these mountains, plant species evolved to inhabit diverse communities found along a steep elevation gradient, across a relatively short horizontal distance (Johnston 1970; Beniston 2003).

In the Central Sierra Nevada, since the 19th century, anthropogenic pressures have increased on montane systems in the form of development, resource extraction, and management policy (SNEP 1996; Potter 1998; Fites-Kaufman *et al.* 2007). Rapid industrialization of resource extraction and development expansion of the 20th century produced unprecedented changes to montane environmental systems which compound our need to understand how species adapt and change over time (SNEP 1996; IPCC 2001; Beniston 2003). Coupled with rapid shifts in climate, as seen within the last half century (SNEP 1996; van Mantgen and Stephenson 2007; Beckage *et al.* 2008; Malmsheirmer *et al.* 2008; Marston 2008), these anthropogenic driven stresses on Sierra Nevada vegetation communities will play an increasingly important role in mountain ecosystems. Given that these recent shifts in climate have taken place over only the last 20-50 years, at an accelerated rate than previously recorded in this region, *how* we detect and monitor vegetation change over time has become an important component to our greater knowledge of ecosystem dynamics (Vale 1987; Klasner and Fagre 2002; Kull 2005).

Historic Data Gaps

> *The most important areas of future research are those centering on relationships between agents of change and vegetation.*
>
> -Fites-Kaufman *et al.* (2007) in
> *Montane and Subalpine Vegetation of the Sierra Nevada and Cascade Ranges*

The complexity of human experience in mountain systems requires multi-faceted change detection research methods across multiple disciplines. Before detailed biological studies of Sierra Nevada ecosystems, the earliest of which date back to the 1930's and 1940's (UCBerkeley 2008), there are few visible and/or landscape scale records to establish benchmarks for long term change detection (SNEP 1996;). John Muir traversed the Sierra Nevada Range chronicling biologic and geologic diversity throughout the late 19th and early 20th centuries (Johnston 1970; NPS 2008). Despite these records we lack a detailed, visibly descriptive record to compare current vegetation growth against. Even within the last 20 years of detailed field study, Fites-Kaufman *et al.* (2007) have noted that site and point scale projects have been over emphasized and landscape scale study has been lacking. There is obviously a need to bridge these gaps between varying scales of study in alpine and subalpine ecosystems.

To fill these gaps, field observations, palynology (pollen), and dendrochronology (tree ring) analysis have been utilized to expand our understanding of vegetation growth across decades and centuries (Vale 1987; Schweingruber 1988; Prentice *et al.* 1991;

Briffa *et al.* 2003). Historic data from these techniques include annual individual growth estimates, historic species ranges, and proxy precipitation and temperature estimates over decades, centuries and millennia (Vale 1987; Schweingruber 1988; Prentice *et al.* 1991; Briffa *et al.* 2003). And while these techniques provide substantial quantitative tools, they lack a detailed qualitative assessment necessary for local and regional investigation of vegetation change(s). Specific location of individual trees, density of forest stands, and range fluctuations of arboreal species are all difficult to determine across extended timelines from narrative, palynology, and dendrochronology.

To establish growth trends along extended timelines, it is important to be consistent in the methods utilized. Recent detailed field observations and studies do not necessarily bridge the gap between historic data retrieved from palynology or dendrochronology and what is observed today. Both of these methods rely on current location of individuals/species, or describe presents/absence, which negates forest/individual health or distribution of species ranges across entire landscapes. Thus, the advent and application of photographic analysis across the previous century provides visual details of individual growth, distribution, and forest stand health unattainable with other methods (Bass 2004). Historic photographs remain unchanged, literal snapshots in time that can be examined and re-examined to address differing research needs across multiple disciplines. Bridging the digital divide (discussed below) has made the storage, retrieval, and analysis of these historic images even easier.

Research Objectives

The objectives of this study are to detail ecosystem change trends in alpine and sub-alpine communities of Yosemite National Park, California, over the last one hundred years (1897-2008) through repeat-photography assessment. A rich photographic history in the upper reaches of Yosemite provides the opportunity to conduct a qualitative assessment of landscape change since the 1890's. The use of repeat-photography, at ~80 different sites across a study area of over 250 km^2, provides a time series of photographs which is used to assess and identify growth trends. No other repeat-photography assessment in this part of the Sierra Nevada Mountains, specifically focused on vegetation change, has spanned such a wide temporal range.

In order for long term assessment of vegetation dynamics to be successful, this study provides repeatable monitoring locations to support future research efforts in Yosemite National Park. The photographic data set was originally discussed in Vale (1987) and Vale and Vale (1994) and was expanded in this 2008 study to 1) add an additional 20+ years of photographic data to the set, 2) expand total temporal reach from ~80 to over 100 years, and 3) provide accurate easily repeatable co-ordinates and meta-data for future study. Five growth trends, including growth and density of Krummholz and forest stands, increased incursion of tree growth into meadows, expansion of forest patches, and a reduction of forest clearings, were tested based on qualitative assessment of photograph triplets taken at each site. It is hypothesized that conclusions reached by other recent studies from the Sierra Nevada and the American West will be seen to continue in the Tuolumne region. Others have concluded that increases in mean temperatures and increased variation in precipitation along with a history of fire suppression policy in the Sierra Nevada, though complex, has produced noted growth of forest stands, expanded range of arboreal species upslope, and increased new growth into meadows (Vale 1987; SNEP 1996; McKelvey *et al.* 1996; Grace *et al.* 2002; Millar *et al.* 2004; Fites-Kaufman *et al.* 2007). Additionally, by increasing accuracy and repeatability, this project has the potential to expand observed trends and establish a baseline for future research. Future applications of repeat-photography at the sites utilized for this study are suggested and discussed. The addition of a quarter century of growth beyond the previous repeat-photography study will provide an update to regional ecosystem change and vegetation growth trends in this area of the Sierra Nevada Range.

LITERATURE REVIEW

Dynamic Landscapes

As the Sierra Nevada Mountains push upward into the path of eastward moving storm systems, orographic forces created temperature and precipitation gradients, resulting in diverse vegetation communities across varying elevations (Beniston 2003). While mean annual temperatures decline relative to elevation, from ~12° C at 1,400 m to ~1° C at 3,400 m at the upper tree line, precipitation changes little across the same elevation gradient (Fites-Kaufman *et al.* 2007). At upper elevations, the amount of precipitation that falls as snow increases dramatically, from 20-25 percent near the lower tree line (1,400 m) to ~95 percent at the upper tree line (3,400 m)(Stevenson 1988 in Fites-Kaufman *et al.* 2007). This availability of moisture, both as rainfall and spring snow melt, plays an important role in the adaptability and success of arboreal species in local plant systems.

The resulting species-diverse alpine and sub-alpine systems respond to different climatic and anthropogenic inputs with varying degrees of adaptability, depending on the dynamic nature of interconnected localized ecosystems (Stohlgren *et al.* 2000; Beniston 2003). In the central Sierra Nevada Range, the landscape is comprised of contiguous and/or intermittent forest stands of largely *Pinus contorta ssp. murrayana*, *Tsuga mertensiana*, *Pinus monticola,* and *Pinus albicaulis*, subalpine and alpine meadows, and vegetation-sparse mountain peaks rising above the tree line (Vale 1987; Fites-Kaufman *et* *al.* 2007; NPS 2008). Each localized system is subject to micro- and macro-climatic influences as well as myriad current and historic anthropogenic disturbances and threats. Slope, aspect, location within the local or larger drainage basin, access to moisture, location within or outside of the Sierra Nevada rain shadow, and minimum and average temperatures each play important roles in the success or failure of different plant species or communities. To address landscape scale change, as suggested by Fites-Kaufman *et al.* (2007), the area of study must traverse a number of these localized climate zones and communities to draw general themes of change.

The 'threats, or the overall 'fragility' of systems, in this study, refers to the rapid onset of direct and indirect anthropogenic driven changes and stresses and the perceived inability of natural systems to adapt and adjust along the same trajectory. Direct anthropogenic stresses to upper elevation habitats in California are wide reaching and can include (but are not limited to) habitat loss and fragmentation caused by development and natural resource extraction (SNEP 1996), the grazing of livestock (Franklin *et al.* 1971; Dunwiddie 1977; Bahre and Bradbury 1978; Vankat and Major 1978; Vale 1987; Taylor 1990; Miller and Halpern 1998), and fire suppression policy (Franklin *et al.* 1971; Vankat and Major 1978; Swetnam 1993; SNEP 1996; McKelvey *et al.* 1996; Murray *et al.* 2000; Butler and DeChano 2001; Vale 2002; Whitlock *et al.* 2003).

For each of five distinct alpine and sub-alpine systems, general trends have emerged to describe the dynamics of high Sierra vegetation growth, which are discussed below (Vale 1987; Vale and Vale 1994).

At the tree line and above

Characterized by stunted growth and wind/snow twisted trunks and branches, the growth of Krummholz stands of mainly *Pinus albicaulis* in alpine environments are greatly influenced by the harsh conditions at or above the tree line. Although the actual elevation of the tree line varies by latitude and region and can be hard to specifically identify (Grace *et al.* 2002), in the Central Sierra Nevada, this 'line' is found at around 2,900 m (NPS 2008).

At the upper treeline, arboreal growth and species' distributions have been in a constant state of flux over previous centuries due to a complex interaction of factors (Foley *et al.* 1994; SNEP 1996; Lloyd and Graumlich 1997). Evidence suggests the location of the tree line has changed, either upslope or down slope, over millennia, and yet we still have an incomplete understanding of what factors are primarily responsible for these major shifts in arboreal species range (Foley *et al.* 1994). Two examples illustrate this dynamic in mountain systems, as well as an apparent uncertainty that exists in scientific thought surrounding these ecosystems. In the first example, Foley *et al.* (1994) argue that 6,000 years ago, variations in Earth's orbit caused northward and upslope elevation expansion of the tree line as a response to increased temperatures, seen mainly at upper latitudes. They base this argument on paleobotanical evidence found at upper elevations. Increases of 2° C were estimated to have driven this expansion of species' ranges. But was temperature alone responsible for mass movement of arboreal species? Conclusions presented in Foley *et al.* (1994) suggest increased temperatures were the root cause, but the complete story is not known. Similarly, Lloyd and Graumlich (1997) argue that in the Sierra Nevada, periods of increased temperatures, punctuated in this case by severe drought events, caused two instances of tree line *decline* during the last 1000 years. Increase in temperature is thought to spur the growth of Krummholz stands during this period while at the same time the lack of moisture on a regional scale limited forest stand expansion (Vale 1987; Lloyd and Graumlich 1997).

While the exact influence climate has on tree line arboreal species is not completely understood, recent study of tree line dynamics suggests upslope and pole-ward movement is apparent, and climate factors are primarily the cause (Hättenschwiler and Körner 1995; Grace *et al.* 2002; Roush *et al.* 2007; Beckage *et al.* 2008). For North American mountains, various temperature models predict increases of 1-5° C which suggests 100 m (Beckage *et al.* 2008) to 700 m (Grace *et al.* 2002) upslope tree line shifts per 100 years over the next century. This is based on current observations and perceived historic arboreal reactions to warming trends (Foley *et al.*1994)

Stevens and Fox (1991) present a number of theories explaining why the growth of trees abruptly ends (forming a ragged 'line') and twisted Krummholz formations exist in these alpine regions. The "winter drought" hypothesis describes restricted growth of individuals by desiccation caused by dry, cold winds acting on branches and leaves protruding from the winter snowpack. Vegetation lower to the ground in these systems is not only protected from harsh winter storms and temperatures, but have been found additionally to have decoupled cellular temperatures and warmer core and branches, from the surrounding ambient air (Grace *et al.* 2002). As vegetation grows above this thin margin of lower wind and warmer temperatures close to the ground, survival of branches and individuals is reduced (Stevens and Fox 1991). This would suggest that increased or decreased depth of winter snowpack would have a great impact on vegetation growth. The success of tree growth is thus hypothesized to be regulated by localized patterns of wind, snowpack, and temperature in alpine regions (Stevens and Fox 1991).

Temperature gradients and their effect on snowpack depths are not the only factors acting on tree species at the highest of elevations in the Sierra Nevada Mountains. Photosynthesis, precipitation, and minimum temperatures are also thought to play a major role in the establishment of a defined tree line. Lloyd and Graumlich (1997), in a dendrochronology study in the southern Sierra Nevada, suggest that tree line elevations were higher throughout the last 3,500 years than what is visible today. They argue that shifts in precipitation, and to a lesser extent temperature, over centuries have had a greater effect on tree line location than shifts in the relative short term. Reduced minimum temperatures and the resulting limit on cellular photosynthesis reduces growth of both additional branches or upward growth of the primary trunk (Stevens and Fox 1991).

A tree's ability to process atmospheric carbon dioxide into usable carbohydrates (at necessary temperatures), annually and/or seasonally, offer additional hypothesis for the cessation of normal growth patterns at a visible tree line and the stunted growth found above (Stevens and Fox 1991). Two theories exist related to carbon cycling and the stunted growth found at and above the tree line, including 1) the "carbon balance" hypothesis that theorizes that there exists an annual imbalance between photosynthesis and cellular respiration, and 2) the "seasonal compression" hypothesis that describes stunted growth due to limits in the length of the growing season (Stevenson and Fox 1991; Shafer *et al.* 2001; Schrag *et al.* 2008). These hypotheses suggest that internal metabolic processes rather than external physical growth barriers restrict individual tree expansion above a certain elevation.

Whereas reductions in snowpack depth during harsh winter months can have a negative impact on vegetation growth, a longer growing season as a result of increased temperatures and earlier snow melt can have very positive impacts on growth (Vale 1987; Shafer *et al.* 1991; Stevens and Fox 1991; Weisberg and Baker 1995; Grace *et al.* 2002). Earlier snow melt combined with increased daily temperatures, as evident throughout the later part of the 20th century (Parmesan 2006; IPCC 2007; van Mantgen 2007), have produced growth of Krummholz formations at upper elevations (Weisberg and Baker 1995; Grace *et al.* 2002). Klasner (2002) concluded, through the use of sequential repeat photography in Glacier National Park, that continuous forest canopy and Krummholz stand density has increased by as much as 3.4 percent over the last half century. If these trends continue, in certain areas (dictated by local conditions), individual tree and branch growth would increase and what were once Krummholz formations would transition to upright forest patches. In these cases the forest stand would be seen to advance beyond the previously visible tree line (Weisberg and Baker 1995).

Tree growth into meadows

Meadows in alpine and sub-alpine systems of the Northwestern United States are found at various elevations and across a number of communities including montane ridge-tops, south-facing hill-slopes, basins, valleys and other poorly drained topography, and the vast parkland of the subalpine zone (Miller and Halpern 1998). In most cases meadows represent unsustainable habitat for tree species, usually too dry or as mentioned, too wet (poorly drained basins). Meadows are a dynamic feature in upper montane systems and arguably more sensitive to geologic, climatic, and anthropogenic driven change than surrounding forest stands (Bahre and Bradbury 1978; Vankat and Major 1978; Allen 1987; Taylor 1990; Miller and Halpern 1998). Although small in size compared to the larger montane forests surrounding them, upper elevation meadows are the richest ecosystems found in the Sierra Nevada Range (Fites-Kaufman *et al.* 2007). In general, meadows are comprised of graminoid and herbaceous species and are found where there is an accumulation of fine-textured soils along with a shallow water table (Ratliffe 1985; Fites-Kaufman *et al.* 2007). A shallow water table is important in that it provides year round soil moisture, which increases growth of grasses and excludes major invasion of arboreal species (Fites-Kaufman *et al.* 2007).

Meadows fluctuate widely as temperatures shift, precipitation patterns change, river/stream systems alter course, and animals/humans interact with grasses and flowering plants (Allen 1987). In Yosemite, changes in temperatures, precipitation, and grazing of livestock have had immediate impacts on meadows (Franklin *et al.* 1971;

Dunwiddie 1977; Bahre and Bradbury 1978; Vankat and Major 1978; Vale 1987; Woodward *et al.* 1995).

Over the last century there has been notable increase in tree invasion into meadows across the Sierra Nevada Mountains and in other locales in the American West (Franklin *et al.* 1971; Dunwiddie 1997; Vale 1987; Taylor 1990; Jakubos and Romme 1993; Woodward *et al.* 1995; Miller and Halpern 1998; Millar *et al.* 2004). In well drained flat areas, not enough moisture can limit tree growth. Conversely, at river or lake margins, or in areas that have poor drainage, too much moisture can limit the ability of trees to grow adequate root systems (Miller and Halpern 1998). In one example, Woodward *et al.* (1995) suggest that over the last century, there has been evidence of tree encroachment in 1) dry meadows and clearings that have experienced wetter than normal weather conditions and 2) in wet areas that were drier than usual. During the mid-20th century, there was an increase in precipitation in the Sierra Nevada coupled with increased average temperatures which some argue are the primary factors driving increased tree growth along meadow margins, especially in areas previously too dry to support arboreal growth (Vale 1987; Talyor 1990; Jakubos and Romme 1993; Miller and Halpern 1995). Meadow ecosystems do not fall into neatly defined categories. The relationship between seasonal precipitation, snow melt, and ground water fluctuations varies greatly by site (Allen-Diaz 1991). The transition from dry to primarily wet meadows has been noted as a precursor to tree invasion and is an important notation to make when looking at areas of possible future tree invasion (Jakubos and Romme 1993).

The cessation of livestock grazing in these alpine and sub-alpine areas is another hypothesis presented to explain a surge in meadow invasion during the 20th century (Dunwiddie 1977; Vale 1987; Taylor 1990; Miller and Halpern 1998; Keeley *et al.* 2003). Alpine and sub-alpine meadows in this part of the Sierra Nevada have evolved along side native grazers including O*vis canadensis* and *Odocoileus hemionus* (Johnston 1970; NPS 2008). The introduction of intense seasonal grazing by large flocks of domesticated species, primarily sheep, reduced the survivability of arboreal saplings in meadows (Keeley *et al.* 2003). Potter (1998) reports that grazing numbers in Tuolumne Meadows reached a peak in the 1870's and 80s with over 12,000 individuals, while others suggest that the size of summer grazing flocks in this part of Yosemite reached into the hundreds of thousands. Livestock grazing, at the scale seen in the late 19th century in the Sierra Nevada, was a new impact on the landscape (Potter 1998). At no other time in the history of this mountain range were the upper montane, sub-alpine, and alpine meadows exploited to this extent by grazing species (Potter 1998). In Yosemite, grazing of sheep ceased in 1905 and an increase of tree invasion into meadows is believed to be the direct result (Vale 1987).

Forest clearings and stand density

The upper elevations of Yosemite and the surrounding region are dominated by stands of *Pinus contorta ssp. murrayana* interspersed with *Tsuga mertensiana*, *Abies magnifica*, *Pinus jeffreyi*, *Juniperus occidentalis* and *Pinus albicaulis* (Johnston 1970;

Vale 1987; Peterson *et al.* 1990; NPS 2008). These forest stands have shown increased density and loss of small clearings across the 20th century (Vale 1987). Millar *et al.* (2004) concluded that there was a positive correlation between annual branch growth and increases in minimum temperature. The increase in individuals (density) and increases of foliage and branches (coverage) is thought to be a direct result of a century of fire suppression policies in addition to increases in precipitation mid century and warming throughout the century (Vale 1987; Peterson *et al.* 1990; Butler and DeChano 2001; Roush *et al.* 2007).

In the Sierra Nevada before the 19th Century, the frequency of fires varied from a few years at lower elevations to over 200 years at upper elevations (Fites-Kaufman *et al.* 2007). In many regions heterogeneous multi-aged forest stands were the product of centuries of fire cycling in sub-alpine systems, where forests were thinned and gaps were opened in the forest canopy. Mckelvey *et al.* (1996) describe the rate of fire return in sub-alpine and alpine arboreal communities as having shifted by one to two orders of magnitude from what they describe as pre-settlement prior to the 20th century and the later 20th century. As man-power and technology allowed, fire-suppression was has been the policy of the National Park from the early 20th century through its peak in the 1970's and 1980's (McKelvey *et al.* 1996). After close to a century of fire suppression policy in Yosemite National Park, a more homogeneous forest exists with denser stands comprised of more shade tolerant species at mid and lower elevations (Fites-Kaufman *et al.* 2007).

While reduced fires and increased precipitation has caused denser forest stands, a lack of natural fire cycling, punctuated by recent increased late growing season droughts, have contributed to tree mortality, and have encouraged large scale parasite/disease infestations in upper elevation tree stands (Fites-Kaufman *et al.* 2007; van Mantgen and Stephenson 2007). Disease and pests have had a presence on the landscape for millennia, but the recent impact of suppression policy has caused conifer forests in the Sierra Nevada Range to show evidence of severe pine bark beetle and lodgepole needle miner infestations resulting in widespread mortality over the past two decades (SNEP 1996; Potter 1998; Fites-Kaufman *et al.* 2007). Fites-Kaufman *et al.* (2007) suggest that stresses caused by air pollution blown west from central and coastal California, intensified by stand crowding caused primarily by fire suppression, leave individuals trees more susceptible to these insect invasions.

Historically, availability of moisture, temperature fluctuations, and natural fire cycling influenced how forests and meadows evolved over millennia. As humans have become an increasing presence on the landscape, natural systems are being threatened. At meadow edges, tree growth created a dynamic forest/meadow boundary which has gone through periods of static no-growth as a result of intensive grazing during the last one hundred and fifty years. When intensive grazing stopped, plant communities again experienced intermittent meadow invasion by trees. Forest stands, once thought to be thinner and more heterogeneous, are becoming denser and more homogeneous since the turn of the 20th century. Denser forests and a lack of naturally cycling fires have increased the prevalence of disease and pest infestation across wide swaths of conifer forest in subalpine forest zones. As conditions within these communities have changed, there have been notable vegetation growth trends visible upon the landscape. And while certain aspects of forest and vegetation community management are within our control (grazing, fire suppression, etc), natural cycling and a changing climate must be continually monitored so that we can understand long term changes that result.

A Changing Climate

> *Mountains in many parts of the world are susceptible to the impacts of a rapidly changing climate, and provide interesting locations for the early detection and study of the signals of climatic change and its impacts on hydrological, ecological, and societal systems.*
>
> \- Beniston (2003)

Since major human settlement began in the Sierra Nevada, there has been a notable trend towards wet, warm, and stable climate conditions compared to the last two millennia (SNEP 1996). Over the last million years, the region has seen eight major glacial and interglacial periods which have shaped and carved the landscape of granite domes, valleys, and mountain peaks (Johnston 1970; SNEP 1996). Within the last 1,200 years, periods of extended droughts have punctuated this general trend of warming and increased precipitation (Vale 1987; SNEP 1996). Climate models predict that the ecosystems at and above 2,400 m will continue to follow trends of warmer and wetter seasons into the next century (Vale 1987; SNEP 1996; Hansen *et al.* 2001; Grace *et al.*

2002). As a whole, the dominant tree species in this region (mentioned previously) have, together, shown evidence of growth and increased stand density as a result of recent regional precipitation and warming trends. Grace *et al.* (2002) predicts that these warmer and wetter climes will cause increased density of existing tree stands and over a larger temporal scale cause upslope movement of species ranges by as much as 100 m per 100 years.

In subalpine, tree line, and alpine communities there are a number of factors that contribute to vegetation growth. While the basics of photosynthesis require sunlight, water, atmospheric CO_2, and warm temperatures for tree growth, there is an increasing consensus among experts that temperature rather than atmospheric CO_2 concentrations is ultimately the limiting factor for tree growth (Klikoff 1965; Grabherr *et al.* 1994; Grace *et al.* 2002).

In an ecological region pressured by the rapid advance of anthropogenic and environmental threats, few disagree about the role that shifts in climate can have on species in mountain systems (Peterson *et al.* 1990; Pauli *et al.* 1996; Parmesan and Yohe 2003; Millar *et al.* 2004; Malmsheirmer *et al.* 2008; Schrag *et al.* 2008). The Intergovernmental Panel on Climate Change (IPCC) has reported that average temperatures in the Northern Hemisphere were higher in the second half of the 20th century than any other 50-year period not only in the last 500 years, but likely the highest in the last 1,300 years (IPCC 2007). In general, average temperatures in mountain systems in North America have risen 1.5°C in the last century (Roush *et al.* 2007). Millar *et al.* (2004) documented an average minimum temperature increase of 3.7°C over the 20th century in the Sierra Nevada Mountains. They noted accelerated warming in two periods, from 1920 to 1940 and from 1976 to 2000. Across the century, average temperatures increased from an average of 3.8°C for the decade of 1910-1920 to 7.5°C for 1990-2000 (Millar *et al.* 2004).

During the 20th century, precipitation varied to a greater degree (see Millar *et al.* 2004). Average precipitation increased 1.5 times (41.7 cm to 63.2 cm) from the second decade (1910 to 1920) to the final decade (1990-2000) of the century (Millar *et al.* 2004). Increases in precipitation after 1975 contributed more to half century averages, as drier periods took place from 1910 to 1935 and from 1945 to 1970 (Millar *et al.* 2004).

In a report prepared for the California Energy Commission, regional models were compared for the Western United States and the result suggested a 3° to 4°C warming trend over the next century (Kim *et al.* 2002; Kiparsky and Gleick 2003). This is significantly higher than predicted global warming trends presented by the IPCC (1.4°–3.8° C) (Kiparsky and Gleick 2003; IPCC 2007). These predicted warming trends will have a greater impact on minimum temperatures than on maximum or average annual temperatures (Kiparsky and Gleick 2003; Millar *et al.* 2004). In upper elevation systems, increases in minimum temperatures can have a greater effect on tree growth than increases in maximum temperatures. This is evidenced by shifting spring snow melt and an increased growing season (Kiparsky and Gleick 2003; Millar *et al.* 2004). Increased temperatures in late winter/early spring or reduction of precipitation in the winter months, or both, can signal important shifts in moisture availability and thus can be predictive for vegetation growth (Stevens and Fox 1991; Fites-Kaufman *et al.*2007). However, warming is not necessarily consistent across the board. Beniston (2003) argues that the spatial resolution of General Circulation Models used to predict climate shifts lack the accuracy to adequately forecast temperature shifts along elevation gradients found with most mountain ranges. To alleviate this discrepancy, Beniston (2003) suggests that the development of 'nested' models would be more appropriate for localized predictions at different elevations and aspect within mountains. Specific to the Sierra Nevada, predictions suggest that the largest shifts in temperature fluctuation will take place in the mountains than any other location in California (Kim *et al.* 2002; Kiparsky and Gleick 2003).

Climate shifts in the later 20^{th} and early 21^{st} Centuries are predicted to continue, and thus monitoring of alpine and sub-alpine vegetation communities becomes an ever increasing necessity. If we are to predict, or attempt to predict, future vegetation shifts as a result of anthropogenic and climate changes, we must understand historic vegetation trends and apply these lessons to future management policy. Repeat-photography methods are aptly placed to fill the gap between varying vegetation change detection methods. Initiated originally largely in the American West, repeat-photography and has become an expanding tool in the new digital world (Kull 2005).

Repeat photography

Geographers have utilized repeat-photography – defined as analyzing photographs taken at different moments in time from the same perspective and location (Kull 2005) – for over 50 years and though little has changed in the basic technique and application of analysis, there has been a noted evolution as new technologies have become available and applied. The method itself has allowed for broad themes to be inferred from comparative case studies of historic and recent photographs, including overlap between management policy, human impacts on the landscape, and climate change. And while comparative analysis has been utilized over a wide range of topics prior to the application of repeat-photography, this technique has evolved to provide detail(s), sometimes unavailable through analysis using other change detection methods, including remote sensing (discussed below), palynology, and dendrochronology analysis as previously mentioned (Vale 1987; Schweingruber 1988; Prentice *et al.* 1991; Briffa *et al.* 2003).

What is Repeat-photography?

Repeat-photography is the analysis of images taken at different moments in time from the same perspective and location (Kull 2005). Simply put, repeat-photography projects are used to visually identify change. Projects can require nothing more than two images spaced at a time interval necessary to detect change for whatever subject(s) desired. Images can be simple photographs or complex remote sensing images taken from orbiting satellites. In many cases repeat-photography projects rely on ‘found’ historic images (see Gibbens and Heady 1964; Hastings and Turner 1965; Vale 1987; Turner *et al.* 2003; Zier and Baker 2006; Roush *et al.* 2007) rather than designed photograph locations and scenes (see Hall 2002).

Advantages

Primarily, this method not only provides visual context to data analysis (Vale 1987; Bass 2004), but also provides detail sometimes not found in historic description or narratives (Gibbens and Heady 1964; Bass 2004; Kull 2005). As a method, this allows for a deeper and more detailed historical reach than most other comparison tools (Kull 2005).

The method is inherently flexible and easy to apply in the field. Compared to other remote sensing or field research methods, repeat-photography is inexpensive (Butler 1994; Kull 2005). While other remote sensing applications might rely on satellite or air-photo flight line time tables, simple repeat-photography projects can be pursued whenever research staff time is available or needed (Vale 1987; Butler and DeChano 2001; Kull 2005). In many cases repeat-photography provides a higher level of detail (including e.g. species type, size, location, etc) from ground-level repeat-photography versus satellite remote sensing or aerial photography (Gibbens and Heady 1964; Vale 1987; Butler 1994; Bass 2004; Kull 2005). This is particularly important in alpine applications where the scale of analysis can be as minute as individual tree growth or tree encroachment on meadows.

Photogrammetric analytical software and methods development have allowed geographers to move beyond qualitative descriptive analysis towards more detailed quantitative and numeric study (Butler and DeChano 2001; Roush *et al.* 2007). Roush *et al.* (2007) utilized GIS analysis tools to add quantitative measurement to oblique repeat-photography. Through the application of powerful analytical tools with the flexibility and low cost of repeat-photography, they identified a 60 percent increase in forest and canopy cover at 12 tree line sites within Glacier National Park.

Limitations

An oblique, ground-level perspective can distort distances, give undue priority to foreground subjects, and obscure important scene items in the background (Bass 2004; Kull 2005; Roush *et al.* 2007). While some see the distinct advantage an oblique angle provides with regards to level of detail (Kull 2005), the distortion of scale (that can exaggerate size or location of objects relative to others) comes at a cost (Bass 2004; Kull 2005). Hall (2002) discusses techniques that can reduce the distortion caused by oblique photography, including heavy reliance on detailed metadata for each photo (exact location, height, lens angle, etc). The distortion found with many repeat-photography projects can start with difficulty in identifying exact on-the-ground locations of previously recorded photographs. Finding these locations can be time consuming and affect the time/budget available for analysis of images. Repeat-photography projects that are designed with site return in mind can mitigate mistakes and distortions by establishing precise and repeatable photo sites.

Another weakness of repeat-photography as a research method is inherent bias (Rogers *et al.* 1984; Bass 2004; Roush *et al.* 2007). Historic images do not represent an 'unbiased statistical sample' of the landscape or subject (Rogers *et al.* 1984). The scientific method prefers controlled environments to conduct research, whereas 'found' repeat-photography includes many variables beyond the control of the researcher. The selection of location, photographic coverage of a certain area, the number of photographs taken, scene composition, and which photos are archived are all limited by the whim of historic photographers, the availability of images, and the discretion of historians and librarians (Bahre and Bradbury 1978; Rogers *et al.* 1984; Bass 2004; Roush *et al.* 2007). Additionally, the qualitative nature of repeat-photography analysis injects uncertainty and inconsistencies into any results taken from these projects. For this study area, the high density of historic photographs is relatively unique and provides for a wide range of potential analysis and comparative study (Vale 1987).

Technological limitations add another level of complexity to this method. Physical variables including camera technology, lens focal length and view angle, and image developing methods all can affect the final output and thus distort or skew comparison studies (Clay and Marsh 2001; Roush *et al.* 2007). Analysis of photograph pairs could be inconsistent due to specific camera settings (e.g. aperture, shutter speed, or film speed) which influence sharpness of image and related sharpness of components of the landscape at different distances, how wide the lens view angle was (e.g. wide angle versus tele-photo), or at what specific height above the ground the camera was positioned. All of this information can affect the resulting images and are rarely included with meta-data accompanying historic photographs (Kull 2005).

Today and beyond

The method of capturing photographs has not changed significantly over the last half century. While the size, weight, and cost of digital photographic equipment has continued to decline since its early use in the latter quarter of the 20th century, the methods of accessing, composing, and capturing images remains largely the same (Roush *et al.* 2007). Digital single lens reflex (SLR) cameras provide almost identical controls and outputs as film and slide cameras did for over a century. What has changed is the ease of processing (all digital) and sharing images in a digital age.

In addition to increased access to digital photograph equipment, the use of light weight, affordable, user-friendly, and increasingly accurate Global Positioning Systems (GPS) equipment has expanded the reliability of repeat-photography. These hand-held instruments are continually becoming smaller, lighter, more affordable, and more accurate. Increased accuracy will result in decreased time spent identifying photographic site locations. Many camera manufacturers are partnering with GPS designers to increase the ease with which GPS coordinates are encoded into digital meta-data associated with each image. A number of these products are on the market today.

Repeat-photography relies not only on successful location of original photo sites, but the reproduction of all photograph variables. Digital cameras now automatically encode meta-data into the digital image files themselves, including exposure, lens angle, ISO, shutter speed, time, date, and in many cases, GPS location (or 'geotagging'). The inclusion of this information will make repeat-photography an increasingly accurate method as each successive site visit will be able to repeat exact location, time/date, as well as camera settings. Greater accuracy of image acquisition will result in increased applicability of quantitative methods such as those discussed in Roush *et al.* (2007) as well as possible applications of multi-spectral analysis (see Crimmins and Crimmins 2008), among others.

Having a cheap, light weight and increasingly easily applied method of monitoring has its distinct advantages when photographing in mountain systems. Digital technology, utilized throughout the repeat-photography process, from in the field through the analysis stages, is expanding the tool kit available to researchers. Photographs provide windows into past eras, which should not be dismissed or seen as anecdotal, but viewed as important additions to change detection. Digital advances provide increased access to historic records, cheaper/lighter/more accurate technologies, and increasingly powerful analysis tools. Newly designed and implemented digital repeat-photography projects could provide a powerful baseline for future monitoring of biologic and geologic systems. It is important that past repeat-photography projects not be lost but serve as a bridge between the pre- and post- digital divide be maintained into the future. In the Central Sierra Nevada, a century of vegetation change detection is just the beginning.

STUDY AREA

The area of focus for this research includes roughly 250 km² of high country in Yosemite National Park, California, in and around Tuolumne Meadows, including areas just outside of the park boundaries to the east (Figure 1). Yosemite (37° 48' N, 119° 30' W), the second national park dedicated in the United States, is located on the western slopes of the Sierra Nevada mountain range in east-central California. This study was conducted in an area loosely bounded by Mount Hoffman to the west, Young Lakes/Ellery Lake to the north, Parker pass/Dana Plateau to the east, and Emeric Lake to the south. The study area includes Sierra Nevada subalpine forest and alpine vegetation zones (Table 1) as described by the National Park Service (2008) (Figure 2).

Table 1. National Parks Service Vegetation Zones
Description and elevations for National Park Service defined vegetation zones for the Sierra Nevada Range along with the number of repeat-photography sites located in each zone.

Zone Name	Elevation	# Photo Sites
Foothill Woodland	Below 899m	-
Lower Montane Forest	900m – 1,799m	-
Upper Montane Forest	1,800m – 2,449m	-
Subalpine Forest	2,450m – 2,899m	52
Alpine Zone	Above 2,900m	31

(Source: National Park Service 2008)

The subalpine forest found in this area of the Sierra Nevada Range replaces the upper montane forest at about 2,450 m (8,000 ft). This vegetation community is characterized by mainly *Pinus contorta ssp. murrayana*, *Tsuga mertensiana*, *Pinus monticola,* and *Pinus albicaulis* surrounding subalpine meadows and granite domes (Vale 1987; Fites-Kaufman *et al.* 2007; NPS 2008). Within Yosemite National Park 297,000 acres (1,200 km^2) of subalpine forest habitat is present (NPS 2008). Sixty-three percent of photo locations used in this study were found here. Located above 2,900 m (9,500 ft), alpine communities are characterized by largely treeless tundra of short grasses, small patches of stunted and dwarfed trees, shrubs, and lichen covered rocks beyond a pronounced tree line. Snow, ice, and wind mark the extended winter, while a short and relatively cool summer allows for a short growing season for any vegetation found at these elevations (Johnston 1970; NPS 2008). Thirty-one photo sites, or 37 percent, were located in the alpine zone.

Figure 1. Study area and photo sites located during 2008 field visits.

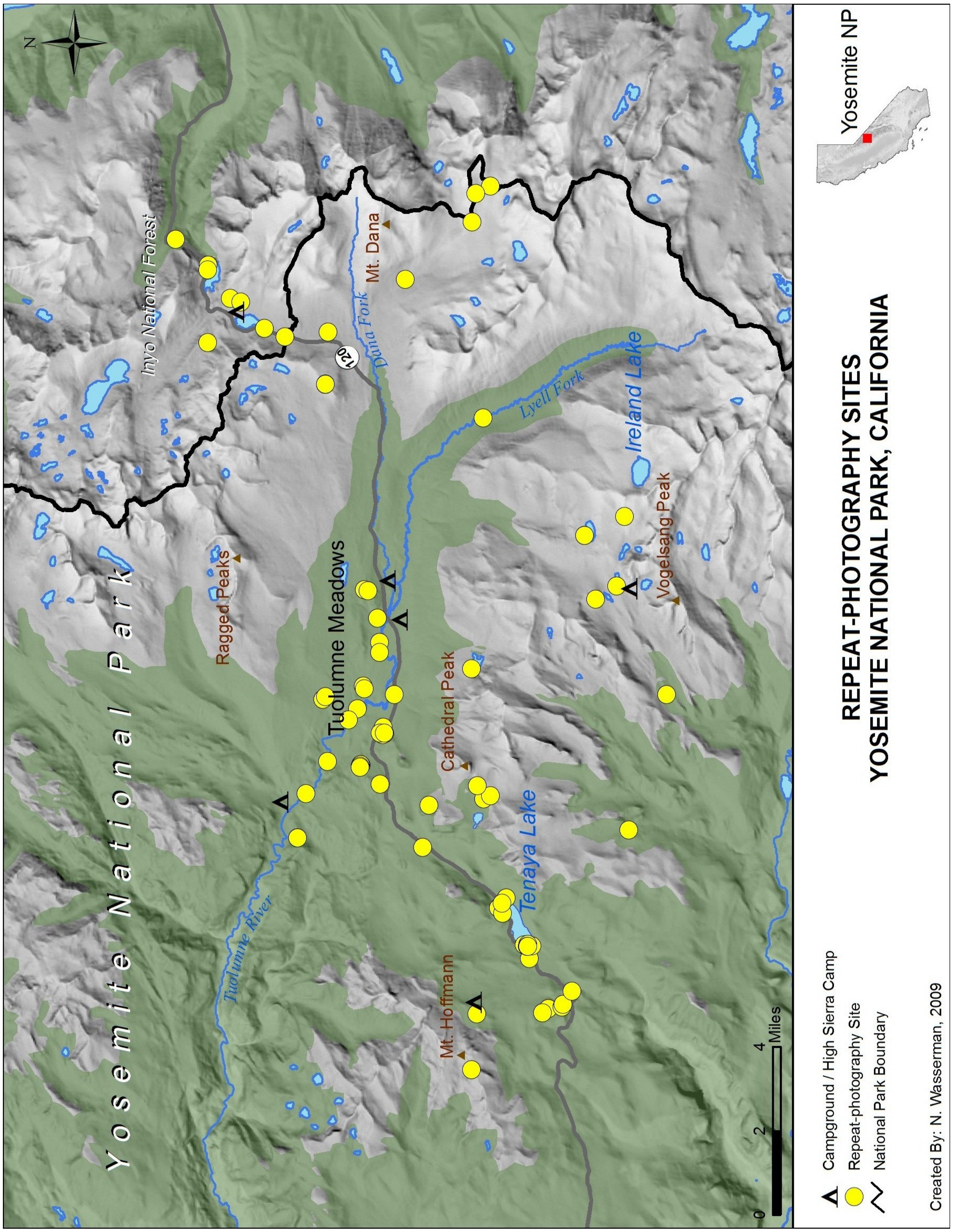
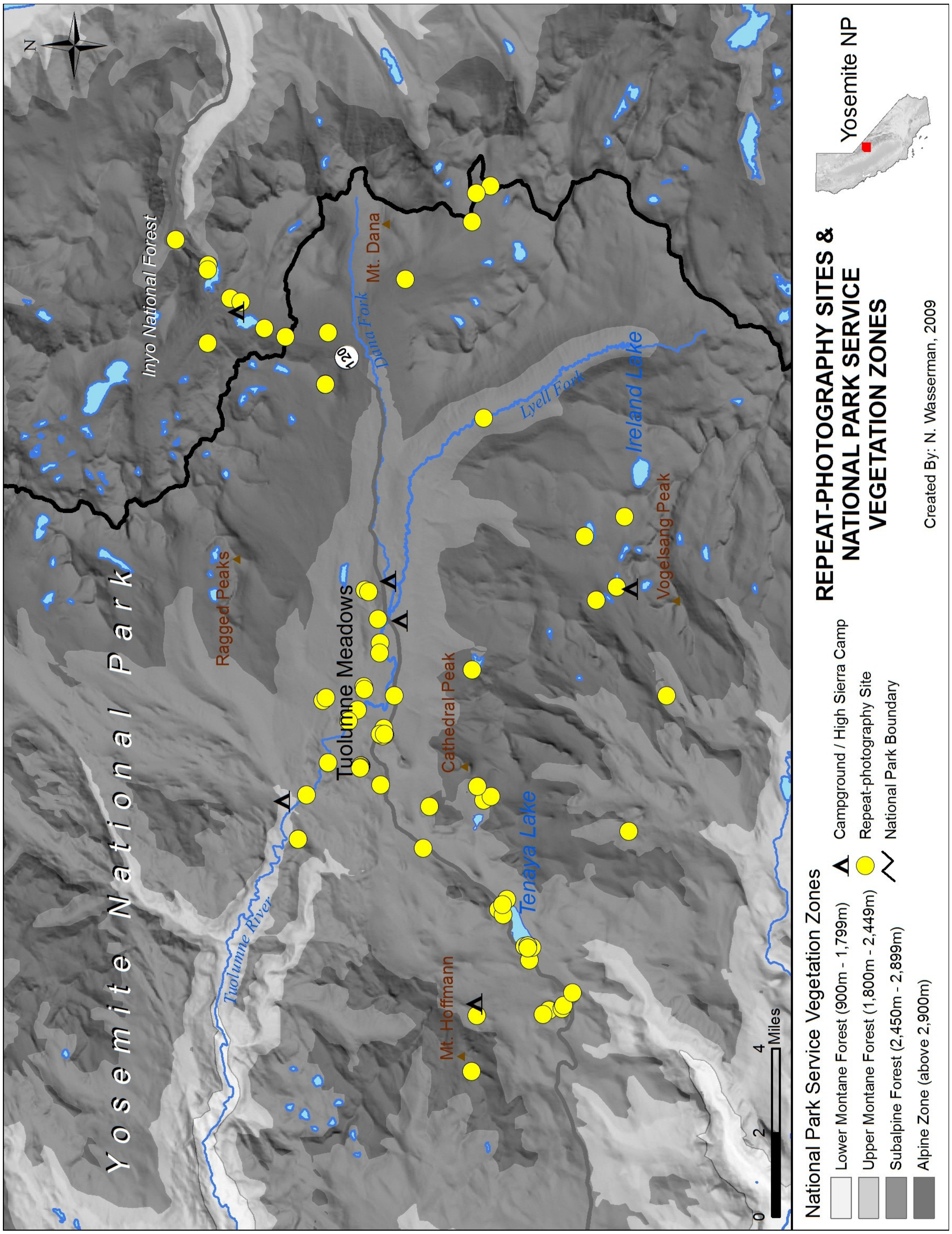


Figure 2. National Park Service forest zones and photo sites.



METHODS

This study uses repeat-photography to identify vegetation growth trends in the sub-alpine and alpine vegetation zones. In order to advance the length of time between paired photographs to capture vegetation growth trends, as well as provide a more detailed description of each site for future monitoring, the photograph sites used and analyzed by Vale (1987) and Vale and Vale (1994) were identified and rephotographed. Vale compared vegetation visible in the 1980's to historic scenes from photographs captured around the turn of the 20th century from the USGS archives. For this 2008 study, photographs captured at each site were analyzed as part of photo triplets: 1) historic USGS photographs taken between 1897-1939, 2) photographs taken by Vale 1984-89, and 3) photographs captured in 2008 (Table 2). The greatest time span of these photograph triplets is 111 years, while the average of the entire data set is 100 years.

Table 2. Photograph Triplets used to identify vegetation change trends
These photograph sets were utilized for this project, including various photographers supplied by the USGS, T. Vale in the 1980's and N. Wasserman in 2008.

Source	Photographer	Photo Year(s)	Cited in text as
USGS	Various	1897-1939	"c1900"
T. Vale	T. Vale	1984-89	"c1985"
N. Wasserman	N. Wasserman	2008	"2008"

Locating repeat-photography sites

Each repeat-photography site was described in Vale (1987), Vale and Vale (1994), as well as within USGS photo captions of the historic photographs. From these general locations and descriptions, topographic features within each photo were reviewed against USGS 1:24,000 scale topographic maps and approximate vantage point(s) were identified.

These approximated locations were then taken to Yosemite during the summer of 2008. Location of exact photo vantage point relied heavily on repeat-photography field methods utilized by the U.S. Forest Service and described by Hall (2002). These include the use of orientation lines, ridgeline alignment, and the identification of foreground features to properly align camera height and field location (Hall 2002). Once each photo location was identified and camera/ tripod set up, the site was recorded using a hand-held Magellan eXplorist 210 Global Positioning System (GPS) unit. The hand held unit was used to record latitude and longitude (WGS84 datum), as well as elevation, direction, and GPS accuracy. Ninety-two percent of sites located were logged with <10 m accuracy, while one-third of the sites were identified to within three meters (Appendix A).

Photographs were captured digitally using a Nikon D60 DSLR camera and Nikon Nikkor 18-135mm (f/3.5-5.6G) DX lens in JPEG format (RBG, 3872x2592px, 300ppi, ~4.5megabytes each) set on a Slik Sprint Pro tripod. Each photo site was bracketed ±1 and ±2 exposure compensation at both f5.6 and f18 in order to record proper exposure, detail, and light composition. In most cases f5.6 provided reliable composition, sharpness, color, and contrast necessary for analysis (Appendix B). Upon review, one frame from each bracketed set was selected, cropped and coupled to their historic pair, and used for all analysis. No digital color or contrast enhancement/correction was applied to any photograph. Low resolution images are included within this text though higher resolution images were used for analysis. A complete set of images, at higher resolution than printed herein, along with an interactive mapping feature are available at http://www.ridgelinephotography.com/Yosemite.htm.

Photo Analysis

Previous work done on this topic by Vale (1987) and Vale and Vale (1994) produced five notable trends apparent in alpine and sub-alpine vegetation zones for this region of the Sierra Nevada. Review of photo triplets for this study was conducted with these trends as a base for analysis. Categories for photo analysis were taken from Vale (1987) and Vale and Vale (1994) include detection of:

1. Change(s) in Krummholz stand height and density
2. Change(s) in forest at the upper forest line
3. Change(s) in tree growth into meadows
4. Change(s) in density of local patches of forest
5. Change(s) of growth patterns of trees on domes and rock slopes

Each 2008 photo was visually compared to its c1985 and c1900 pair separately, though in some cases no c1985 photo was available and thus the 2008 photograph was compared to c1900 photos only (Appendix C). In most cases, increase/decrease in the number of individual trees (forest stand density) vs. increased/decreased branch/foliage growth within stands (coverage) was indistinguishable, and thus an assessment of overall ‘density/cover’ was conducted. The net result is evidenced by fewer or reduced spaces between trees, less exposed rock or slope between stands, visibly fuller and healthier looking individuals, and a more homogenous and dense forest stand as seen from a distance.

In general particular attention was paid to overlap between photos to avoid ‘double counting’ features or events. Forest stands, slope faces, and meadow edges (for example) if pictured in two or more adjacent pictures taken by the same photographer and in the same year were only recorded once. If a similar vantage point or field of view was taken in different years, these were included as separate events. A value of *increase* (“+”), *decrease* (“-”), *no change* (“/”), or *not visible/not applicable* (“nv”) was assigned to a subset of criteria within each of these categories.

Krummholtz formations

Review of Krummholz formations was broken into three sub-categories: Individual height, stand density, and individual tree branch/foliage health. Height was reviewed relative to foreground objects (usually rocks/boulders) and in some cases other vegetation in the area, though this was avoided if possible. In most cases qualitative growth of individual trees could be easily assessed, either taller/bigger, smaller, or the same. Visual increase in the number of individual trees and increase/reduction of gaps between trees was used to determine stand density (as previously mentioned). If individual trees could be discerned from the larger grouping, changes in size of branches and overall evidence of tree health - fuller, “bushier” branches vs. skinnier, thinner branches and foliage - was determined.

Tree line stands

Photographs including the tree line were reviewed against both the c1900 photo set and the c1985 photo set (when available) in order to assess growth at the tree line over differing time spans (25 yrs vs. 100 yrs.). As discussed, movement of the tree line can be difficult to detect due to the growth of saplings intermixed with dwarfed trees at the tree line ecotone. When compared relative to ridgelines, predominate rock features and other stationary objects, tree line movement was determined based on 1) increased density of the forest stand immediately at the tree line, along with 2) increased presence of tree growth beyond that line. These assessments were done on areas that theoretically could support tree growth, meaning where there was a visible continuation of soils on slopes or ridges and not in areas where abrupt steep slopes existed that do not/could not support tree stand growth. As with Krummholz formations, if individual trees could be identified, the health of these individuals was taken into consideration. There were few instances of this though, mainly due to the fact that most photographic scenes that included the tree line were from vantage points far afield from the tree line itself.

Meadows

In photo triplets that contained meadows, four criteria were assessed. First, was there evidence of any new tree growth in areas that previously did not contain trees? If there was an increase in trees in the meadow, a designation of “increase” or “+” was recorded. Second, was the original meadow edge (relative to ridgelines, foreground objects, etc) still visible or had tree invasion obscured/retreated from this edge? This helped to establish ‘substantial’ meadow invasion where the original meadow edge was completely obscured. Lastly, while assessing new growth into meadows, notice was taken of non-arboreal growth in the scene. The growth of grasses and non-woody vegetation, though seasonally variable, was included in review to help assess soil moisture as well as help define a base-line for future analysis. Inclusion of analysis of non-arboreal vegetation is not included in discussion but was noted during review of the photograph triplets.

Forest stands

Qualitative assessment of forest stands, not at the tree line and distant from meadow edges, was based on visual evidence of stand density, included the reduction/expansion of non-meadow forest clearings, the increase/decrease of forest patches, and increased/decreased branch and foliage cover. In most cases it was difficult to determine whether there were more/fewer individual trees present *and/or* if there was increased/decreased cover of branches and foliage. Thus, forest stands were assessed for their density and cover. During the review of photograph triplets that contained forest stands, it was noted that there were large areas of tree die-off. Die-off was characterized by visible concentrations of de-foliated and/or snags within a continuous forest stand. Discoloration of individuals or forest canopy towards browns and grays helped to identify these areas.

Domes and rocky slopes

Though containing thinner stands of trees, domes and talus/rocky slopes were visible in many photo scenes and included in review. Two criteria were used to describe these areas. First, a general analysis of increased/decreased individual trees and the presence/absence of clearings were conducted (previously discussed as stand ‘density’). Visually, increases in the number of trees on domes and rocky slopes could be qualitatively assessed fairly easily. In particular, new growth was visible where seasonal snow patches once existed, the spaces between individuals was reduced, and evidence of stand expansion was apparent for smaller patches of trees. Second, were young tree saplings visible? Saplings, normally a quarter the size or less of surrounding trees could be important in establishing growth rates as well as providing evidence for cycles of germination in the region.

Snow patches

In the case of visible patches of snow, size relative to surrounding landmarks, ridgelines, and prominent boulders was assessed. Each patch was reviewed against their historic partner(s), and a designation for the entire scene was concluded. This analysis and inclusion of data is designed for future study and did not result in conclusive discussion in this study.

Eighty-eight percent of the photo sites used by Vale (1987) and Vale and Vale (1997) were identified and rephotographed for this study. Those sites excluded were either not locatable, too far afield, or contained minimal usable scenery. Combined, the located photograph sites were found across over 900 m (3,000 ft) of elevation across an area 250 km^2. The location of these sites would not have been possible without the work presented in Hall (2002) and should be consulted if future repeat-photography projects are attempted or designed. In Yosemite National Park and the surround area, repeat-photography has allowed assessment of vegetation change across over one hundred years of landscape change.

RESULTS & DISCUSSION

This study was able to identify, locate and photograph 88 percent of the photo scenes within the study area from the original work done by Vale (Vale 1987; Vale and Vale 1994). Fifty-two photo locations were identified above 2,450 m in the subalpine forest zone, and 31 were located above 2,900 m in the alpine zone. Evidence of vegetation change was analyzed between the three photo sets, c1900, c1985, and 2008. Based on 83 located and photographed scenes, five vegetation growth trends identified by Vale (1987) were documented and confirmed in addition to one new trend, reduction in snow fields. For each category at least two photo triplets are provided*. Discussions of results primarily compare photographs taken in 2008 to those taken c1985 unless otherwise noted. If no historic photograph was available, " - " is included in the associated table. In upper elevations of Yosemite National Park and the surrounding area, vegetation growth trends identified and discussed in the late 20th century (see Vale 1987) have continued through the beginning of the 21st century.

Changes in Krummholz stand height and density

Krummholz stands of mainly *Pinus albicaulis* in alpine environments above the tree line showed a general trend towards increased individual height and to a lesser extent increased density of stands, consistent with Vale's (1987) findings (Table 3).

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* The complete set of photograph triplets, at higher resolution than printed here, is available on the attached CDROM or at http://www.ridgelinephotography.com/Yosemite.htm

Krummholz stands were visible in 9 photo sets and reviewed against c1985 photos in all cases except photo #1 where no c1985 photo was available (Table 3). Of these, 67 percent (6 of 9) showed individual height increases and 55 percent exhibited increases in stand density (Figure 3). No change in stand density was detected in one third of those photographs reviewed (Figure 4). When foliage growth and health of individuals was visible, 60 percent showed evidence of increased coverage of individual branch and foliage growth while no change was detected in the remaining 40 percent. Compared to other data sets within this study, Krummholz formations comprised a small portion of photo sites and thus the conclusions presented should be noted with caution and further research in this area pursued. Krummholz stands found in the study area exhibited growth patterns consistent with trends identified by Vale (1987) and those found in other regional studies (Klasner and Fagre 2002; Millar *et al.* 2004).

Table 3. Krummholz Photo Analysis
Repeat-photography analysis of photo sets containing Krummholz formations. Photos compared c1985 and 2008 unless only c1900 photo available or otherwise noted. Visual change between photograph pairs identified as increase ("+"), decrease ("-"), no change ("/"), or not visible/not applicable ("nv").

Photo #	Area	Elevation (m)	Only c1900 photo available	Contains krummholz	Indiv height (+, -, /)	Stand density (+, -, /)	Indiv branches/foliage cover (+, -, /)
1	Tioga Pass	2985	x	y	nv	+	nv
5	Tioga Pass	2976		y	+	+	+
9	Gaylor Lake	3257		y	+	/	/
10	Gaylor Lake	3257		y	+	-	nv
13	Gaylor Lake	3257		y	-	/	/
14	Gaylor Lake	3257		y	+	/	+
59	Vogelsang	3097		y	+	+	nv
71	Parker Pass	3324		y	+	+	+
89	Mono Pass	2982		y	nv	+	nv

Figure 3. Results - Increased individual and stand Krummholz growth
Photo #71, from a view southeast through Parker Pass at 3,324 m, both height and increased branch/foliage cover of foreground Krummholz formations are visible.

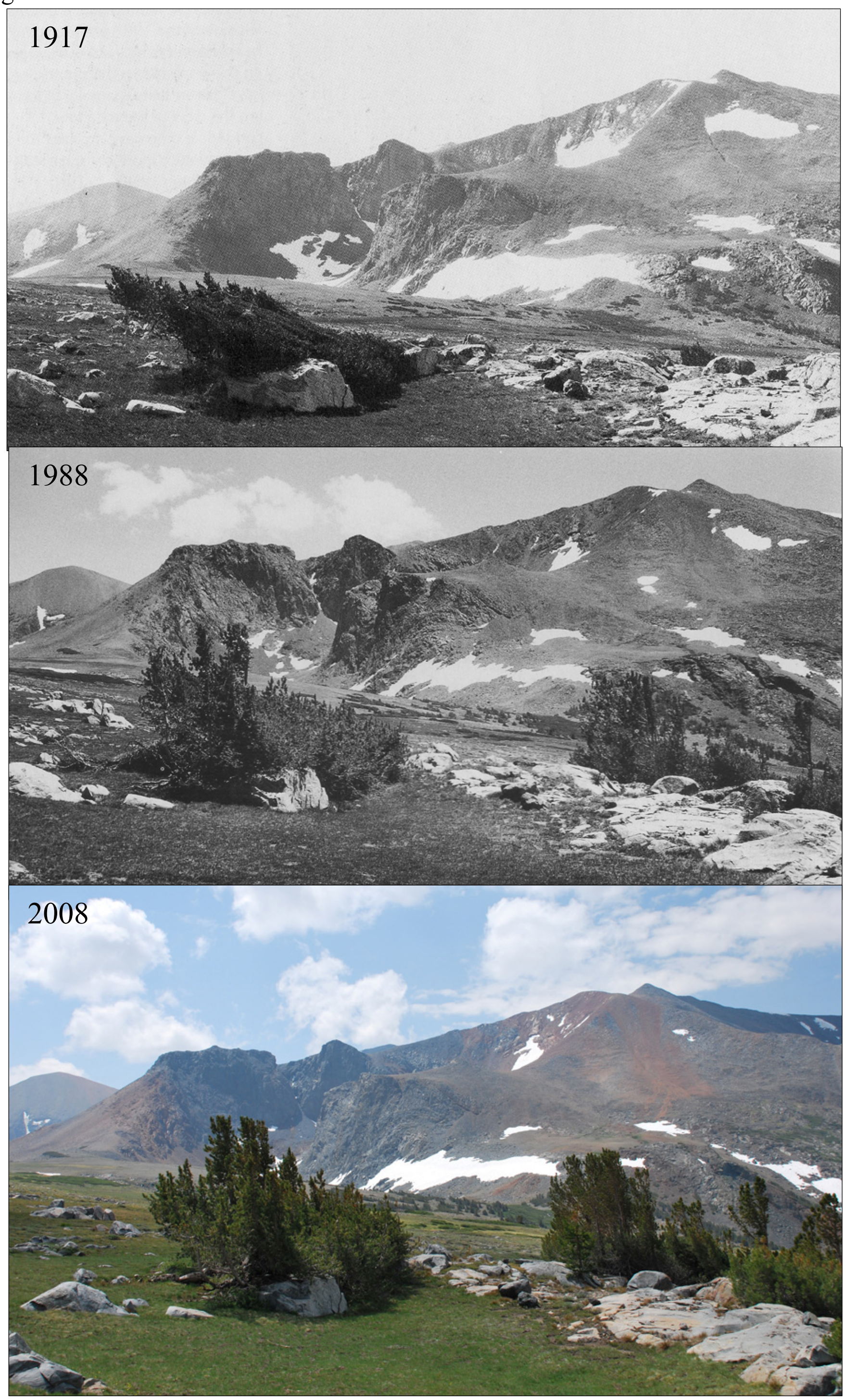
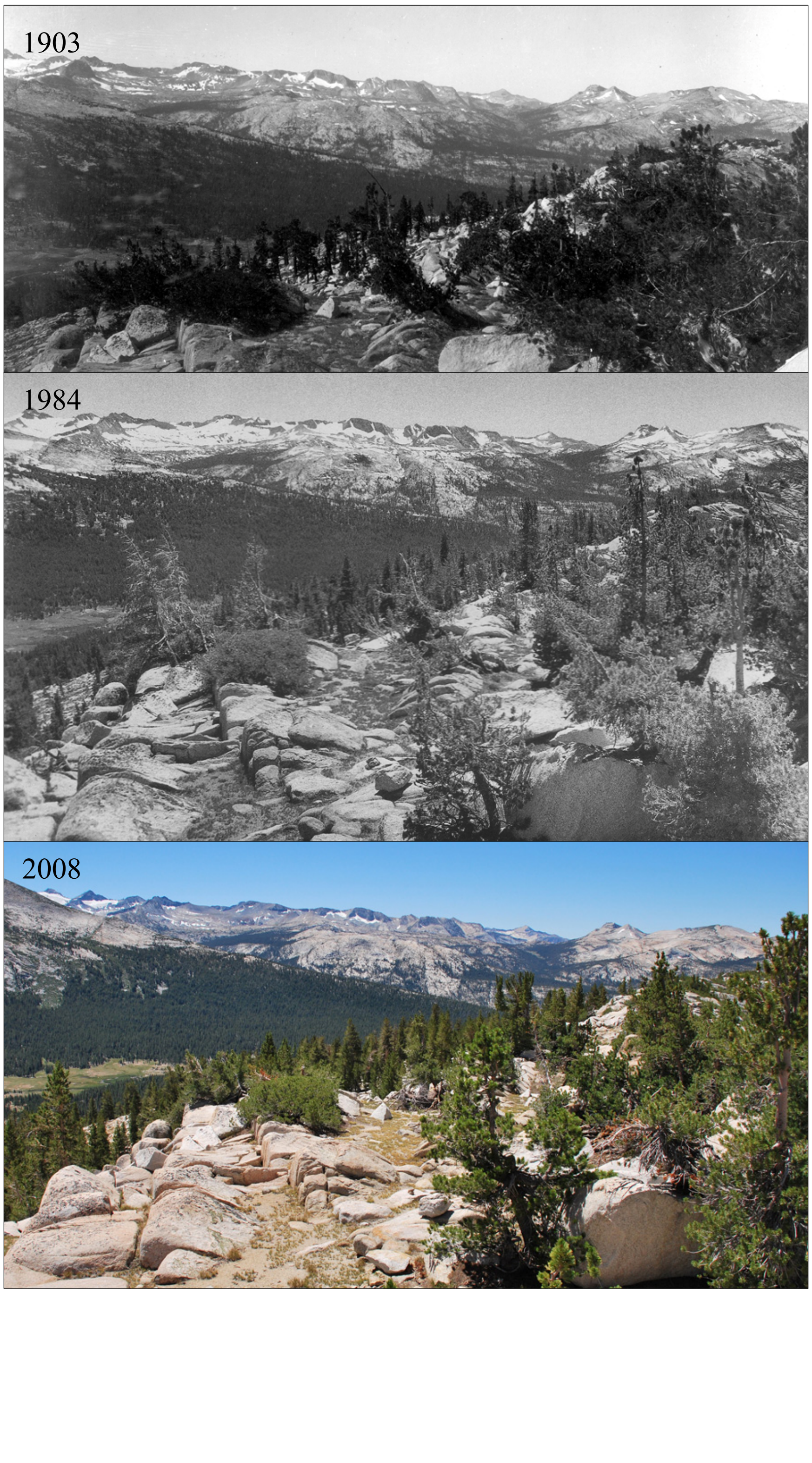


Figure 4. Results - No apparent change in Krummholz
Photo #14, looking southwest from the ridge above Galyor Lakes, at 3,257m. While some individual trees have grown, some have fallen, and many remain stunted. No major growth change is clear between 1984-2008 photos.



Increased average minimum temperatures, a lengthened growing season, and increased availability of moisture have been identified as drivers of growth seen at and above the tree line (Vale 1987; Stevens and Fox 1991; Klasner and Fagre 2002; Millar *et al.* 2004). Though the results of this study do not identify one or more of these drivers specifically, the overall growth trend visible in the photo triplets mirror similar findings found in other regions of the Sierra Nevada. If upper elevation temperatures continue to warm as predicted (see Kiparsky and Gleick 2003; Millar *et al.* 2004), growth of existing trees, emergence of new saplings, and overall growth Krummholz formations will provide important indicators of change within alpine vegetation communities.

The twisted branches of *Pinus albicaulis* and other alpine tree species remain in these wind-swept areas for decades, even centuries in some cases (Weisberg and Baker 1995). To further our understanding of upper-elevation vegetation dynamics it is important that the lifespan of live individuals be tracked and documented over an expanding time-line. While clear findings of increased height and density of Krummholz stands are concluded, further study is necessary to better understand weather and climate conditions and their impact on upper elevation tree stands. Future study of these specific stands could include metrics of growth of individuals and branches. For example, in Figure 3 the height of foreground rocks could be measured to estimate historic growth and establish benchmarks for future growth rates or decline of specific individuals. The photo sample set used in this study was relatively small as compared to others and thus would warrant further monitoring and expanded research of Krummholz formations in the region.

Change in forest stands at the upper tree line

Ninety percent (18 of 20) of photos where the tree line was clearly visible showed evidence of increased density of the forest stand (Table 4 & Figure 5). In most cases, individual branch and foliage assessment was not possible because this level of detail was not visible at the distances photographed (Figure 7). There are numerous theories concerning increased forest stand density at the tree line. For example, evidence of direct anthropogenic drivers such as the cessation of logging is seen in Figure 5, while the less specific affects of environmental/climatic cycling and possible fire regime policy could be potentially explanations of the changes visible in Figure 6. In general, increased stand density at the tree line seen across this data set would confirm increased density trends discussed by Vale (1987). Vale (1987) concluded that increased density of forest stands at the treeline was apparent c1900-c1985.

While Vale had reported little evidence of upslope movement, when you compare c1900-2008 there is evidence of upslope movement of the treeline. Only 30 percent of the photo sites visited in 2008 (6 of 20) demonstrated upslope movement of the treeline since c1985 whereas seventy-five percent of photo sites showed evidence of upslope treeline movement over the past century (Figure 7). This high percentage across the entire study area confirm conclusions of recent vegetation studies of tree line dynamics

(Grace *et al.* 2002; Klasner & Fagre 2002; Roush *et al.* 2007*)* and suggest further research is needed to establish quantitative methods to track and measure tree line movement over time. As mentioned, Vale (1987) did not conclude upslope movement of the treeline was visible, while this study concludes that upslope movement of the treeline is indeed evident across the timeline of photograph review (1897-2008). Consistency of photo analysis is important (same technician used for all review, etc) though this is not always possible. As a qualitative research method, these discrepancies can be expected to a certain extent. It is hoped that the meta-data from each photo triplet and repeat-photography site will be re-examined and reassessed into the future.

Additional measurements taken in the field could provide important metrics (i.e. stand size and measurement of tree line movement over time) to establish consistency of trend analysis. Pairing terrestrial GPS positions of landmarks and visual tree line with aerial or remote sensing images, along with oblique repeat-photography could advance our understanding of tree line dynamics. Study plots or tree core samples within viewsheds of these repeat-photography sites would also help to establish a localized historic story of vegetation change. Specifically, the high level of accuracy demonstrated with improved digital methods for this project would support the application of quantitative methods such as those utilized in Rouch *et al.* (2007). Quantitative measurement of tree line location as well as changes in forest canopy cover could be possible. While alternative methods have been suggested (see Hall 2002 and Roush *et al.* 2007), interdisciplinary cooperation between remote sensing, biogeography, and vegetation management would lead researchers to a greater understanding of change in alpine systems over time.

Table 4. Treeline Photo Analysis

Repeat-photography analysis of photo sets where the tree line was present. Photos compared c1985 and 2008 unless only c1900 photo available or otherwise noted. Visual change between photograph pairs identified as increase ("+"), decrease ("-"), no change ("/"), or not visible/not applicable ("nv").

Photo #	Area	Elevation (m)	Only c1900 photo available	Visible Treeline	Noticeable movement v. c1900 (+, -, /)	Noticeable movement v. c1985 (+, -, /)	Stand density at treeline (+, -, /)	Indiv health/cover (+, -, /)
2	Tioga Pass	2953		y	+	/	+	nv
3	Tioga Pass	3009		y	+	+	+	+
5	Tioga Pass	2976		y	/	nv	+	+
8	Tioga Pass	2992		y	+	+	+	nv
10	Gaylor Lake	3257		y	+	/	+	+
11	Gaylor Lake	3257		y	+	+	+	nv
12	Gaylor Lake	3257		y	+	+	+	nv
13	Gaylor Lake	3257		y	/	/	+	nv
14	Gaylor Lake	3257		y	+	/	+	nv
15	Gaylor Lake	3257		y	+	+	+	nv
17	Gaylor Lake	3257		y	+	+	+	nv
18	Gaylor Lake	3257		y	/	/	+	nv
22	Lyell Canyon	2687		y	+	/	+	nv
24	Tuolumne Meadows	2854		y	nv	/	/	nv
28	Pothole Dome	2622		y	/	/	+	nv
32	Tioga Road	2776	x	y	+	nv	+	nv
66	May Lake	2746		y	+	/	+	nv
78	Tuolumne Meadows	2614		y	+	/	+	nv
89	Mono Pass	2982		y	+	/	+	nv
94	Sunrise	2860		y	+	/	/	-

Figure 5. Results - Increased forest stand density
Photo # 89, view south from silver mining ghost-town of Bennettville at 2,982m. Increased density of individual trees at the tree line is evident in this area, most likely a result of the reduction/ending of logging in the area. The buildings visible in 2008 are maintained for tourism purposes by the Forest Service.

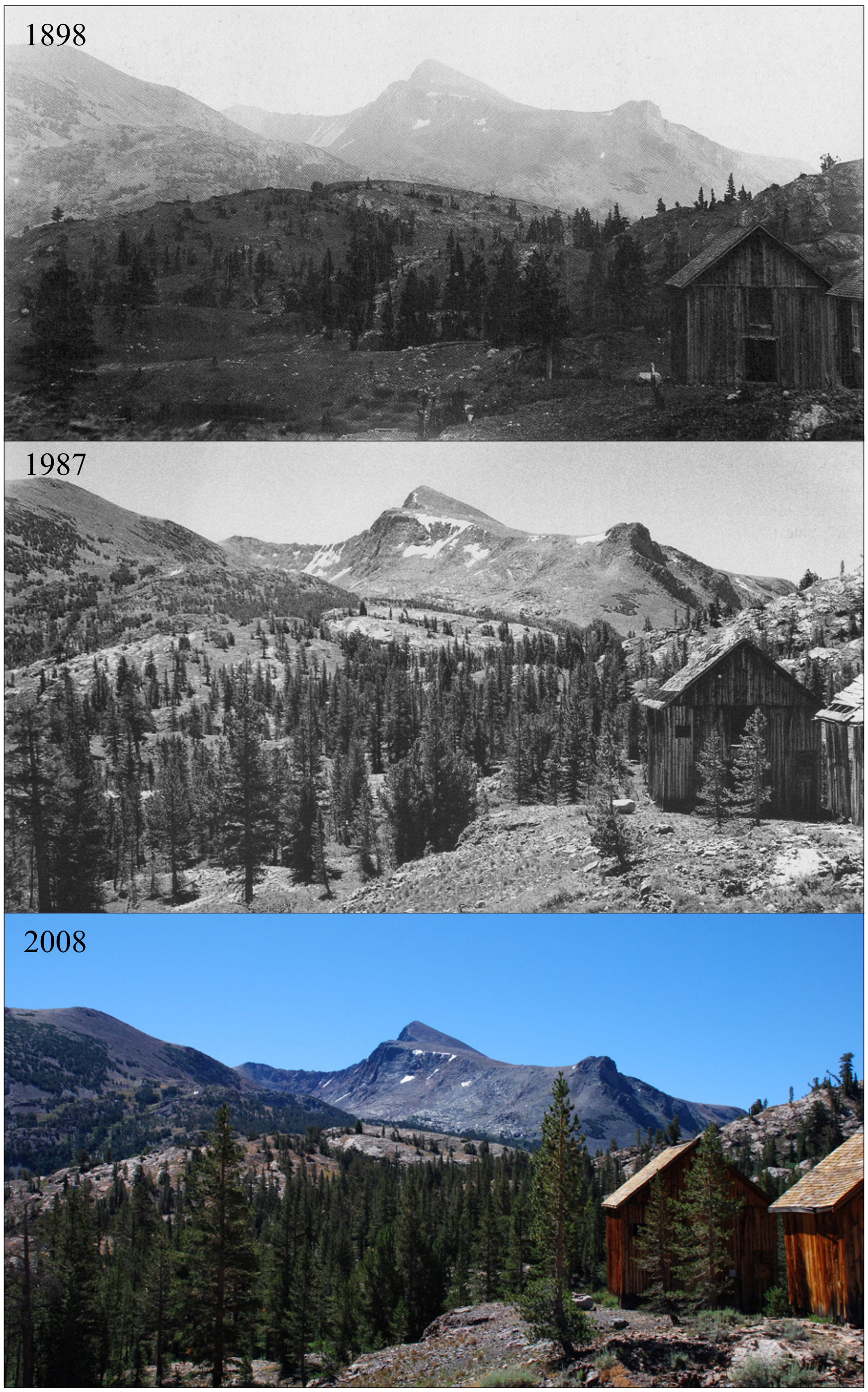


Figure 6. Results - Increased individual health
Photo #10, increased branch and foliage growth is visible in foreground stand in this view looking east along the Gaylor Lake ridge at 3,257m. Across the valley on the flanks of Mt. Dana, tree line stands are visible.

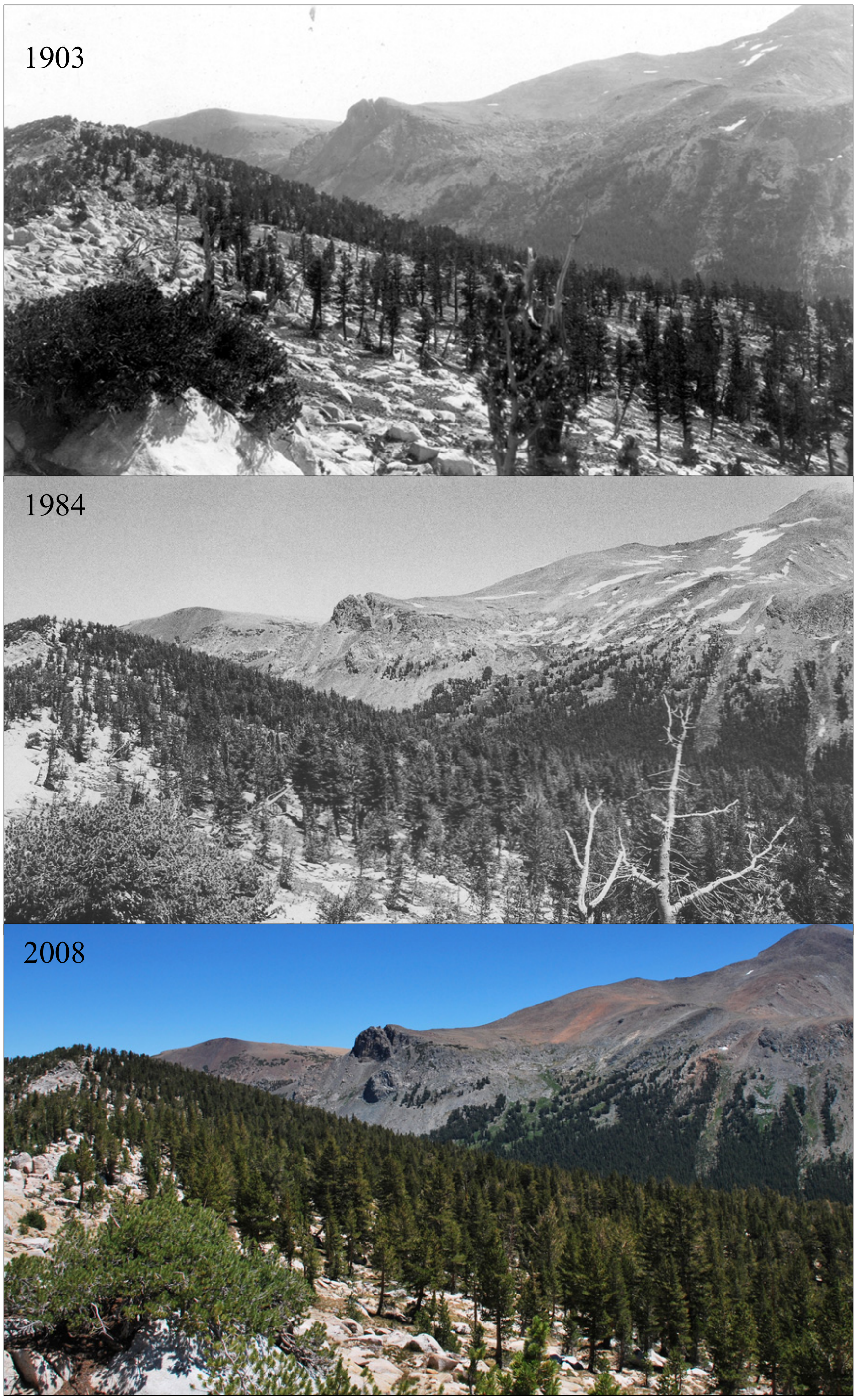
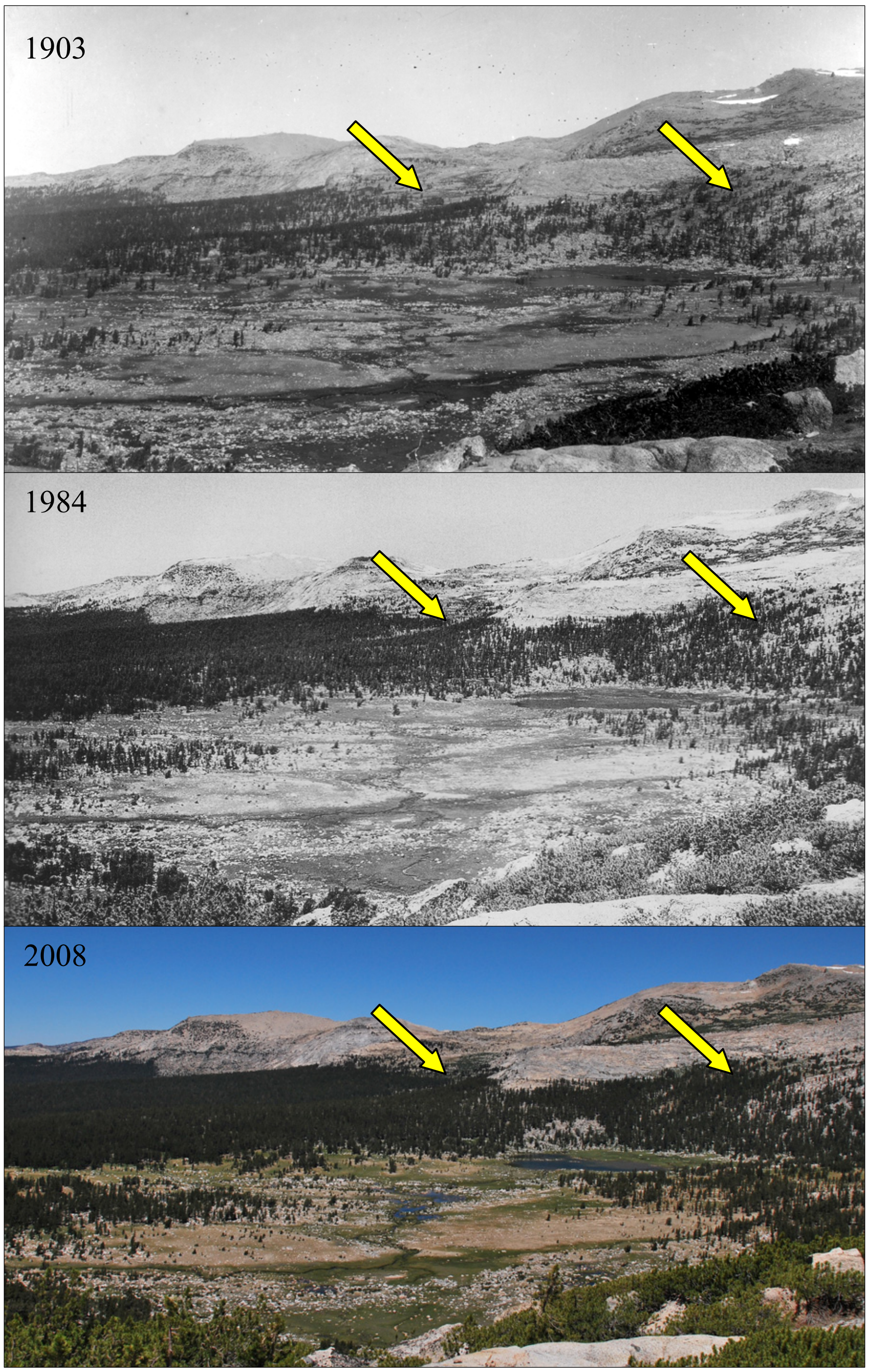


Figure 7. Results - Upslope movement of the tree line
Photo #17, a view northwest across the Gaylor Lakes Basin.Vale (1987) concluded no upslope movement of the tree line was evident, but when compared across 105 years of growth, evidence of upslope tree growth (although slight) can be seen. Arrows indicate areas of increased stand density and highlight upslope movement of tree line.



Changes in tree growth into meadows

Within the study area, there was significant evidence of tree invasion into meadows (Table 5). Vale (1987) found that of the 32 photos he analyzed showing meadows, 94 percent (30 photo sites) showed evidence of tree invasion. Tree growth in and around meadows since c1985 reveals 57 percent (20 of 35) of photo sites exhibiting growth beyond the meadow edge[†] (Figure 8) and the remaining 43 percent (15 of 35) of photo scenes exhibiting little or no clear evidence of changed growth into meadows (Figure 9).

While increased tree invasion into meadows was evident between c1900 to c1985 and c1985 to 2008, the most substantial meadow invasions were seen by comparing c1900 to 2008 (Figure 10). In instances of substantial growth, the encroachment of individuals from meadow edges completely obscured previously unencumbered views across meadows and/or of distance ridges and peaks (Figure 11). This had the potential to hinder site location, in particular Vale (1987) site #53 which was not located in 2008 due to tree growth into the meadow and obscured view of surrounding ridges and peaks.

[†] Encroachment along meadow edge relative to tree growth further into or across meadow(s) is noted as a precursor to more extensive meadow invasion.

Figure 8. Results - Increased tree invasion into meadows
Photo #22, along the Lyell Fork of the Tuolumne River, looking south east at Potter Point (right). Growth of established trees and new saplings is visible between 1984 and 2008.

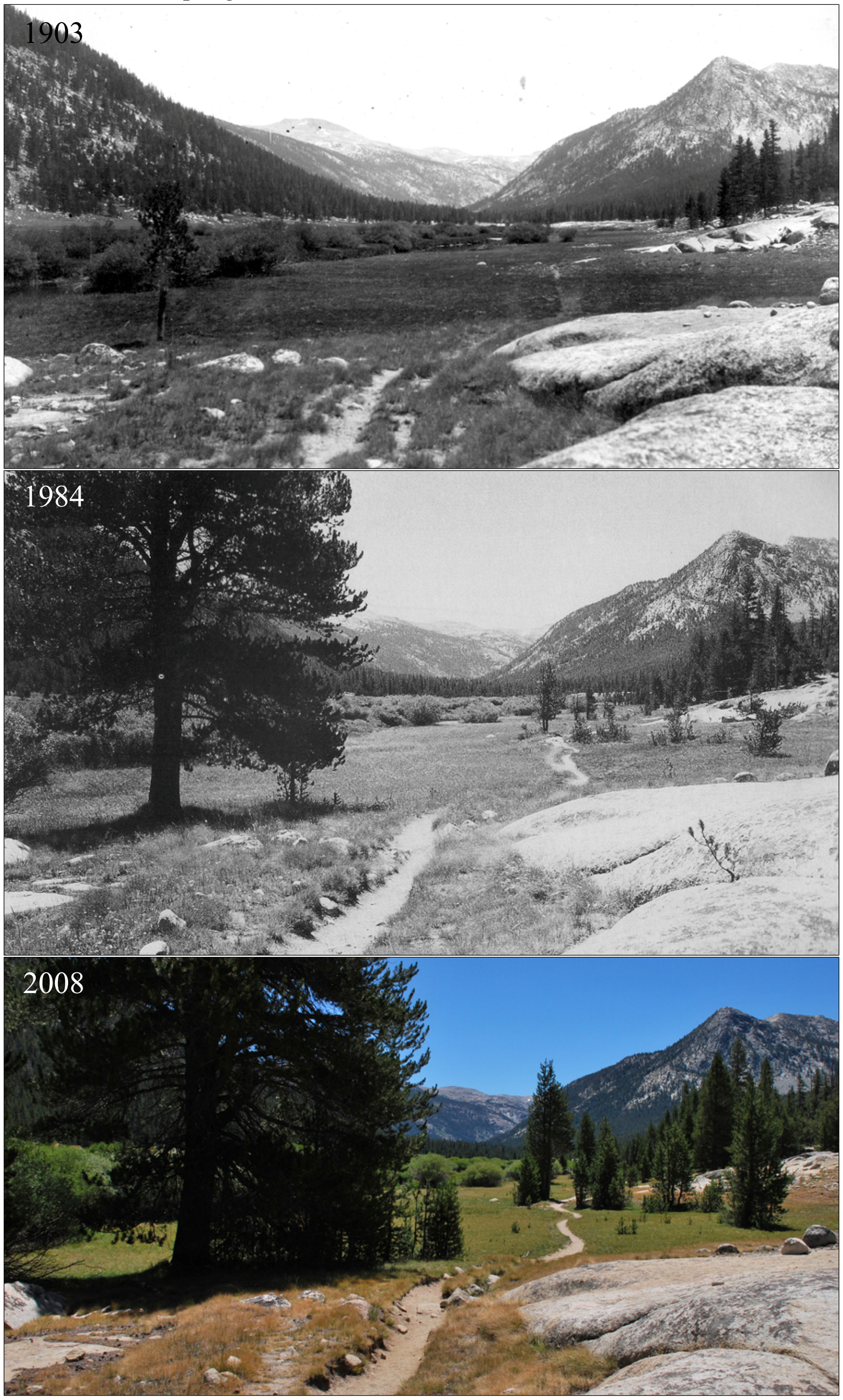


Table 5. Meadow Photo Analysis

Repeat-photography analysis of photo sets containing meadows. Photos compared c1985 and 2008 unless only c1900 photo available or otherwise noted. Visual change between photograph pairs identified as increase ("+"), decrease ("-"), no change ("/"), or not visible/not applicable ("nv").

Photo #	Area	Elevation (m)	Only c1900 photo available	Meadows Visible	Invasion (+, -, /)	Meadow edge visible (+, -, /)	Non-arboreal vegetation (+, -, /)
3	Tioga Pass	3009		y	+	+	+
4	Tioga Pass	3024		y	+	+	/
5	Tioga Pass	2976		y	+	+	+
8	Tioga Pass	2992		y	+	+	+
11	Gaylor Lake	3257		y	+	+	nv
12	Gaylor Lake	3257		y	+	+	nv
13	Gaylor Lake	3257		y	+	+	/
14	Gaylor Lake	3257		y	+	+	nv
16	Gaylor Lake	3257		y	+	+	+
17	Gaylor Lake	3257		y	+	+	nv
18	Gaylor Lake	3257		y	+	+	nv
19	Parker Pass	3393	x	y	/	/	+
20	Parker Pass	3462		y	/	/	/
22	Lyell Canyon	2687		y	+	+	+
24	Tuolumne Meadows	2854		y	+	+	nv
26	Tuolumne Meadows	2627		y	+	nv	-
27	Tuolumne Meadows	2636		y	/	/	+
28	Pothole Dome	2622		y	+	+	nv
29	Pothole Dome	2616		y	/	/	nv
30	Pothole Dome	2621		y	/	/	nv
32	Tioga Road	2776	x	y	+	+	nv
33	Tioga Road	2776		y	+	+	nv
34	Tioga Road	2778	x	y	+	+	nv
36	Tuolumne Meadows	2619	x	y	+	+	nv
45	Tenaya Lake	2533	x	y	+	+	nv
50	May Lake	3308		y	/	+	nv
51	Cathedral Lake	2918		y	+	+	nv
52	Cathedral Lake	2933		y	+	+	/
54	Elizabeth Lake	2898		y	/	/	nv
56	Vogelsang	3152	x	y	/	/	nv
57	Vogelsang	3152	x	y	/	/	nv
58	Vogelsang	3158	x	y	+	+	+
59	Vogelsang	3097		y	/	/	+
60	Vogelsang	3361	x	y	+	+	+
61	Vogelsang	2856		y	+	+	/
62	Tuolumne Meadows	2609		y	+	+	/
63	Pothole Dome	2621		y	/	/	/
67	Tuolumne Meadows	2625		y	/	/	-
68	Parker Pass	3023		y	/	/	nv
71	Parker Pass	3324		y	/	/	nv
76	Tenaya Lake	2618		y	/	/	+
78	Tuolumne Meadows	2614		y	/	/	/
92	Tuolumne Meadows	2621		y	+	/	/
94	Sunrise	2860		y	+	+	nv

Figure 9. Results - Meadow edges unchanged
Photo #78, the west end of Tuolumne Meadows looking south with Cathedral Peaks in the background. Areas of meadow edge (right) show no change since 1988, whereas other areas (left, further down meadow) show evidence of meadow invasion away from the edge.

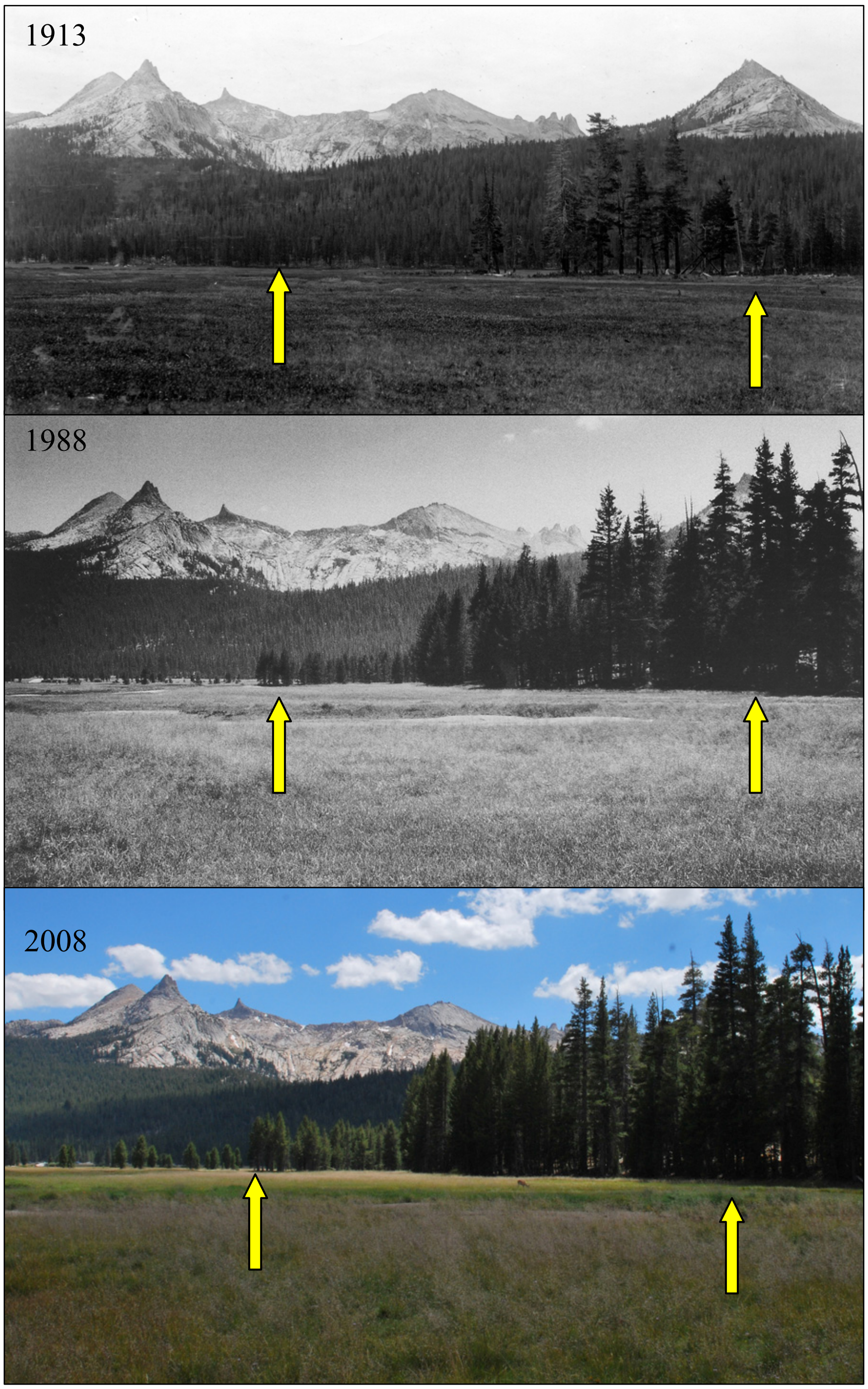


Figure 10. Results - Meadow Invasion
Photo #62, view of Fairview dome across the western end of Tuolumne Meadows demonstrating tree invasion into the meadow from the forest stand to the left (east).

Figure 11. Results - Obscured view due to substantial growth
Photo # 68, near the junction of Spillway Lake and Mono Pass trails, the distant ridges and foreground objects are obscured by substantial growth of the forest stand as it moves into the meadow valley. The large dark rock visible in the 1917 image is noted in subsequent photos.

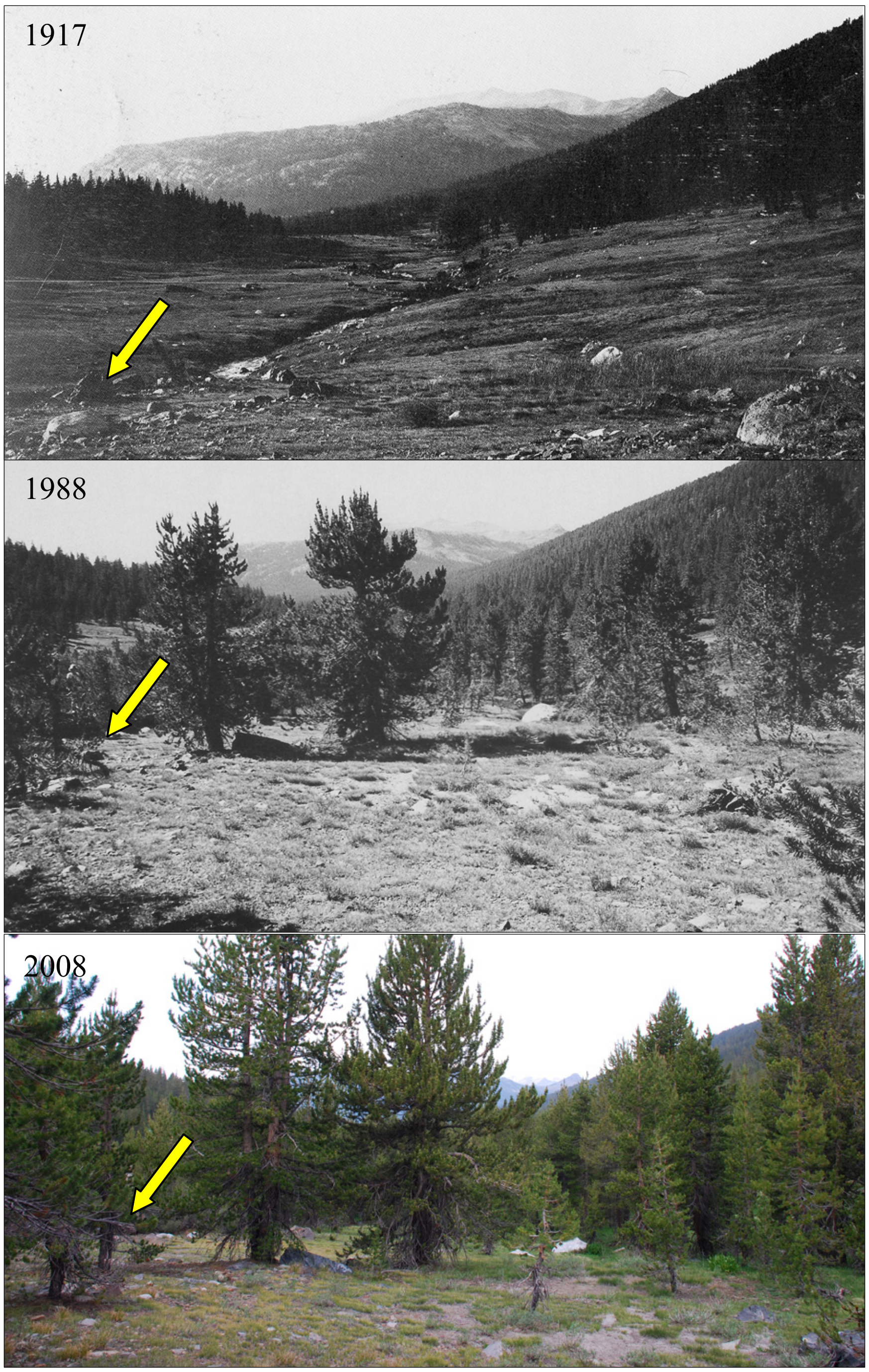
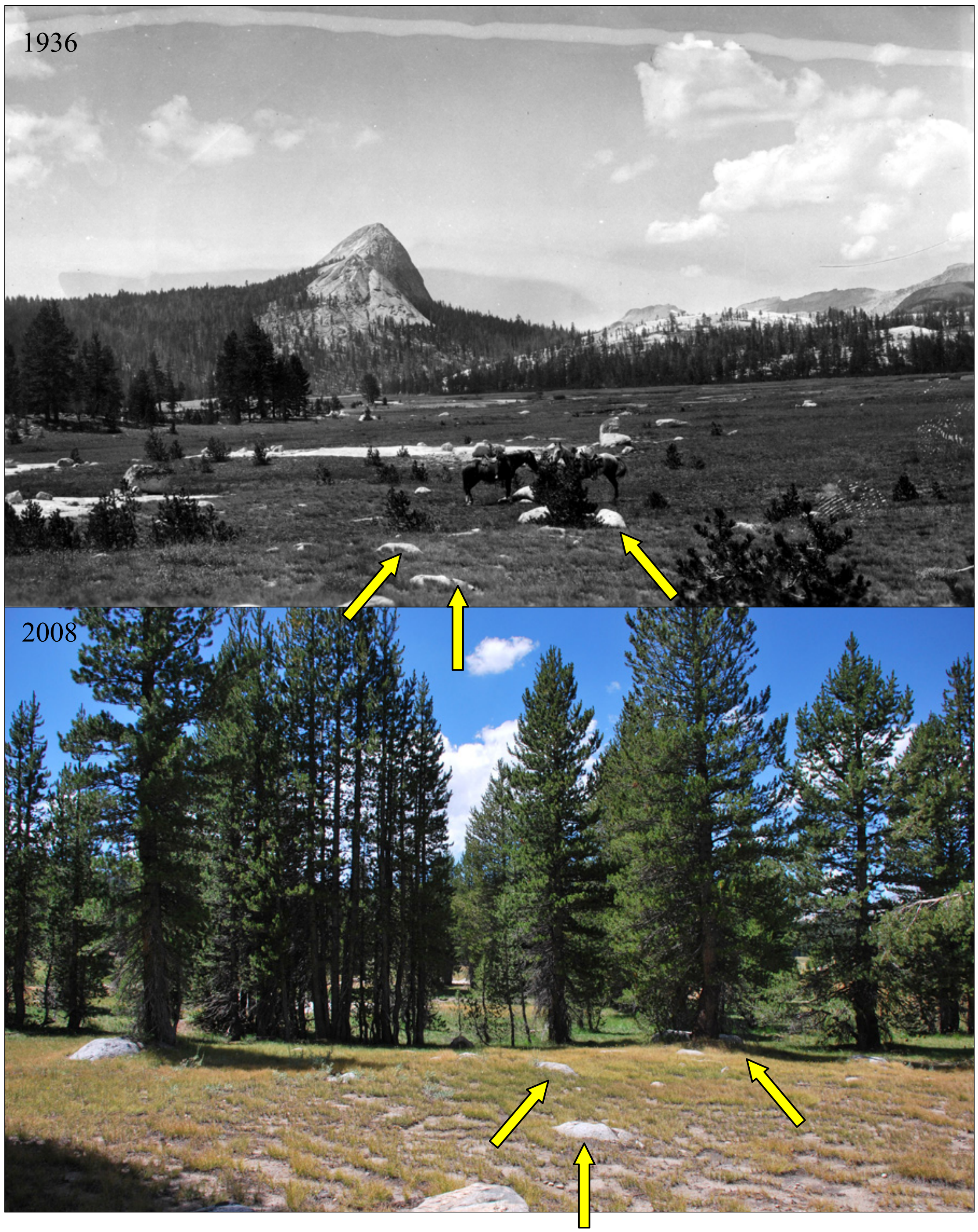


Figure 12. Results - Meadow invasion obscuring scene
Photo #36, looking southwest across Tuolumne Meadows towards Fairview Dome. The three foreground boulders are noted, particularly the set on the right with the tree growing between them. These benchmarks were key in discovering this site. No c1985 photo was available for this scene.



These photo comparisons show invasion of meadows by trees has continued in the Tuolumne Meadows area. In the short term (c1985-2008) there has been notable tree growth along meadow edges and over a century of change, there are numerous examples of substantial tree invasion. Across the Sierra Nevada, the causes of tree encroachment into meadows vary and cannot be neatly defined (Ratliff 1985; Fites-Kaufman *et al.* 2007). Some argue that cyclical climatic patterns, both seasonal shifts in precipitation and water table levels, have the greatest impacts (Fites-Kaufman *et al.* 2007), while others postulate that the removal of grazing (Franklin *et al.* 1971; Dunwiddie 1977; Bahre and Bradbury 1978; Vankat and Major 1978; Vale 1987; Taylor 1990; Miller and Halpern 1998), and/or increased fire suppression have allowed for increased tree encroachment.

Without a clear understanding of what factors or what combination of factors have the most impact, further study into meadow feedback loops is needed. Study plots and survey measurements within the viewshed of these repeat-photography sites could be utilized in future studies to enhance the qualitative data available with specific quantitative measures.

Changes in density of local patches of forest and forest clearings

Forest clearings have decreased and forest patches have increased, resulting in denser forest stands (Figure 13). Vale (1987) identified 13 photo pairs that exhibited increased forest density in areas away from the tree line and removed from meadow edges. When comparing c1985 to 2008 photos, 63 percent (26 of 41 photos) exhibited evidence that forest clearings had decreased and overall density had increased (Table 6 and Figure 14). In the case of photo #96, the forest stand is visible but there is not enough detail to determine a change in stand density or reduction in clearings. Similar findings of increased forest density have been suggested within the Sierra Nevada (SNEP 1996; Lloyd and Graumlich 1997; Potter 1998; Millar *et al.* 2004; Fites-Kaufman *et al.* 2007) and across the American West (Hutchinson *et al.* 2000; Murray *et al*. 2000; Butler and DeChano 2001; Klasner and Fagre 2002; Zier and Baker 2006).

As discussed, fire management and precipitation cycles are thought to be the main contributing influences to increased forest stand density (Vale 1987; Peterson *et al.* 1990; Butler and DeChano 2001; Roush *et al.* 2007). Cyclical fire regimes clear the understory, remove woody debris from the forest floor, remove pests and/or diseased trees from stands, and open holes in the canopy which encourages growth of diverse tree species thus forming a heterogeneous forest stand (Millar *et al.* 2004; Fites-Kaufman *et al.* 2007). Together, periods of drought coupled with extended periods between fires can result in higher susceptibility of wide spread and more intense fires (Millar *et al.* 2004).

Figure 13. Results - Reduced forest clearings
Photo #33, view northeast across the Tuolumne River and the northwestern end of Tuolumne Meadows. In this view, denser forest stands and filled in forest clearings are visible.

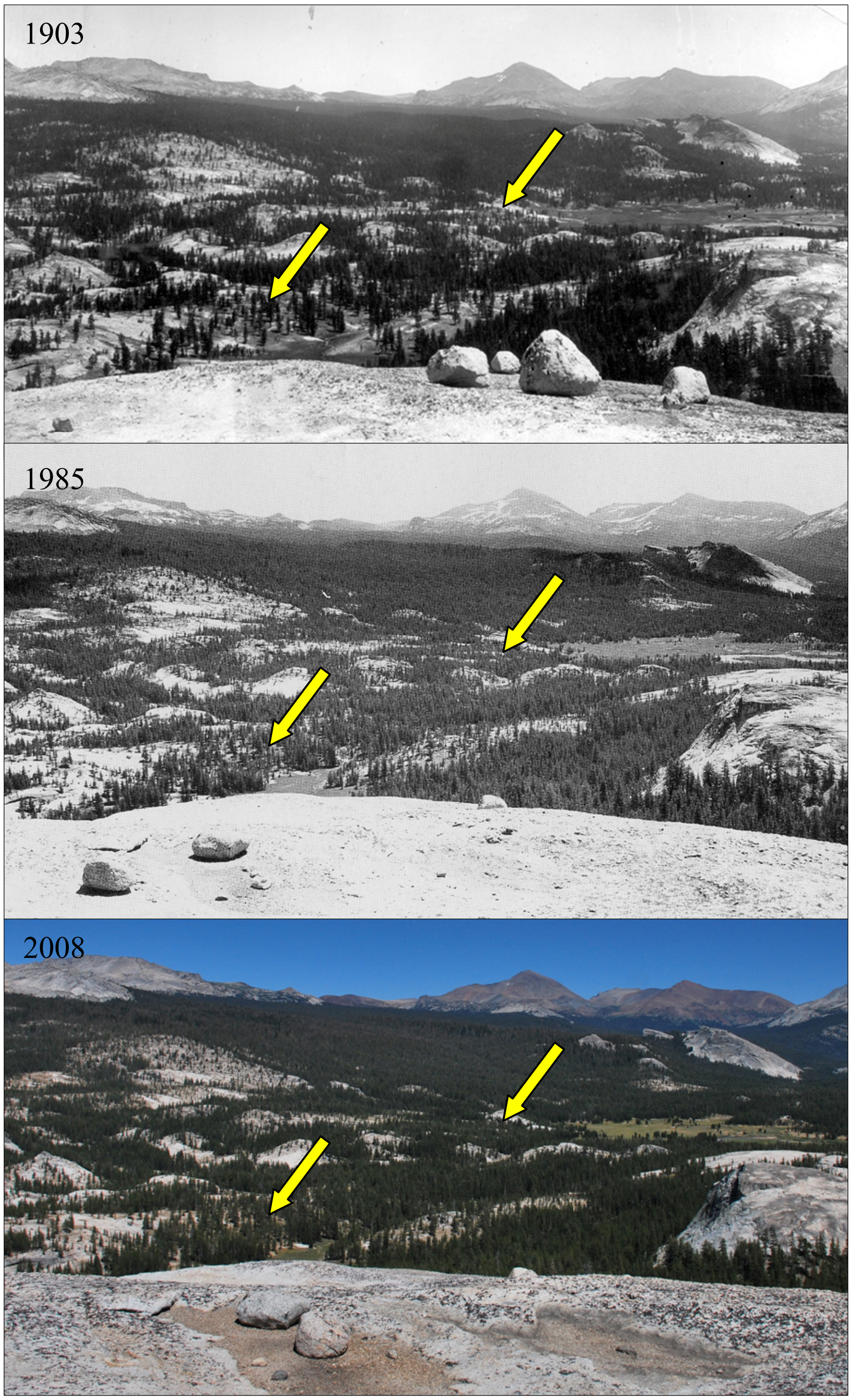
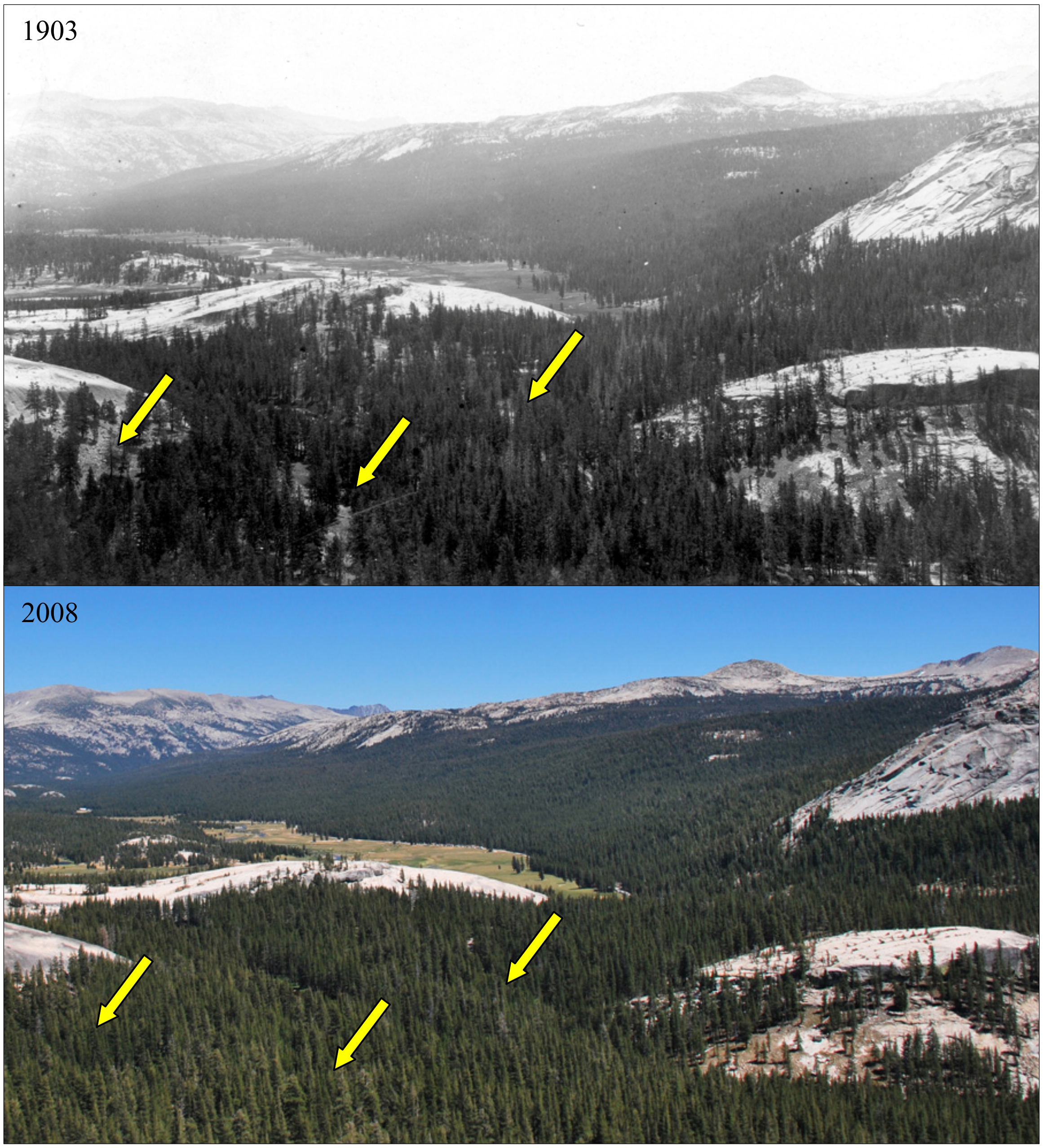


Table 6. Forest Stand Photo Analysis
Repeat-photography analysis of photo sets containing forest stands. Photos compared c1985 and 2008 unless only c1900 photo available or otherwise noted. Visual change between photograph pairs identified as increase ("+"), decrease ("-"), no change ("/"), or not visible/not applicable ("nv").

Photo #	Area	Elevation (m)	Only c1900 photo available	Forest Stand Visible	Density/ Cover (+, -, /)	Visible die off
2	Tioga Pass	2953		y	+	
3	Tioga Pass	3009		y	+	
4	Tioga Pass	3024		y	+	
8	Tioga Pass	2992		y	/	
9	Gaylor Lake	3257		y	+	
10	Gaylor Lake	3257		y	+	
13	Gaylor Lake	3257		y	+	
14	Gaylor Lake	3257		y	+	
15	Gaylor Lake	3257		y	+	
16	Gaylor Lake	3257		y	+	
17	Gaylor Lake	3257		y	+	
18	Gaylor Lake	3257		y	+	
22	Lyell Canyon	2687		y	+	
31	Pothole Dome	2634		y	+	
32	Tioga Road	2776	x	y	+	
33	Tioga Road	2776		y	+	
34	Tioga Road	2778	x	y	+	
35	Tioga Road	2784	x	y	+	
38	Glen Aulin	2663	x	y	+	
40	Glen Aulin	2663	x	y	+	
41	Glen Aulin	2663	x	y	+	
42	Young Lakes	2729		y	/	
44	Cathedral Lake	2990	x	y	+	
45	Tenaya Lake	2533	x	y	+	
46	Tenaya Lake	2535		y	+	
47	Tenaya Lake	2489	x	y	+	
48	Tenaya Lake	2493		y	/	
49	May Lake	2807		y	+	
50	May Lake	3308		y	+	y
51	Cathedral Lake	2918		y	+	
52	Cathedral Lake	2933		y	/	
54	Elizabeth Lake	2898		y	+	
56	Vogelsang	3152	x	y	+	
57	Vogelsang	3152	x	y	+	
58	Vogelsang	3158	x	y	+	
60	Vogelsang	3361	x	y	+	
61	Vogelsang	2856		y	+	y
62	Tuolumne Meadows	2609		y	/	
64	Tioga Road	2655		y	+	
66	May Lake	2746		y	+	
68	Parker Pass	3023		y	+	
74	Tenaya Lake	2588		y	/	
76	Tenaya Lake	2618		y	/	
79	May Lake	2855		y	/	
82	Glen Aulin	2502		y	/	
89	Mono Pass	2982		y	+	
90	Young Lakes	2691		y	+	
91	Tioga Pass	2779		y	-	
94	Sunrise	2860		y	/	y
96	Tenaya Lake	2566		y	nv	
99	Tenaya Lake	2529		y	/	
100	Tenaya Lake	2488		y	/	
101	Tenaya Lake	2495		y	+	y
102	Tenaya Lake	2495		y	-	

Figure 14. Results - Increased forest stand density
Photo #32, a view east across Pothole Dome (center-left) and western Tuolumne Meadows. The forest stand appears denser and lacks small clearings visible in the 1903 photograph (noted with arrows). In this case, no c1985 image was available.



In four distinct locations (7%), there was visible evidence of large scale tree die-off (Figure 15 & Figure 16). Extended patches of apparently dead and/or dying trees can have numerous causes including disease/pest infestation and areas of recent fires. In the Sierra Nevada, different species of bark beetle have become a widespread threat to alpine and sub-alpine forests due to increased density of forest stands, the lack of cyclical fire regiments, and increased drought intensity (see Ferrell 1996; Fites-Kaufman *et al.* 2007).

This photo set could be used to monitor the spread of disease/pest infestation and/or document post fire succession. From these four identified areas of die off, causality could not be determined (Pest? Fire? Disease?) and thus continued monitoring of die-off extent is suggested. Future study could include continued monitoring and assessment of stand health, pre- and post-disturbance monitoring, and canopy cover estimates.

Figure 15. Results - Forest stand health
Photo #94, Long Meadow adjacent to Sunrise High Sierra Camp, with Columbia Finger in the distance. While tree growth into the meadow is evident in this triplet, there is not enough detail to determine forest stand density (mainly due to obscured view in 2008). Important to note, this view provides an example of large scale die-off (see Figure 16).

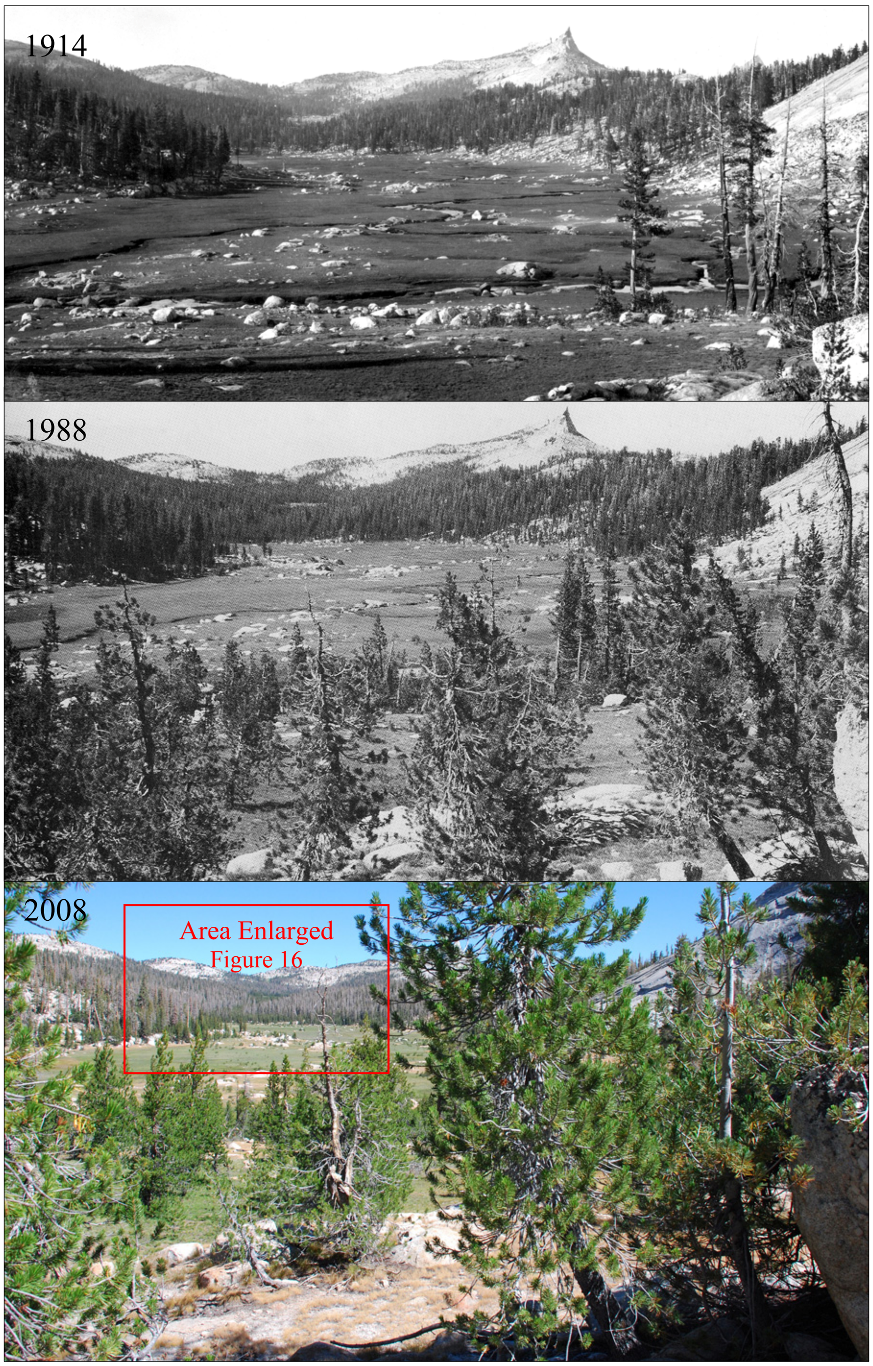


Figure 16. Results - Areas of substantial tree die-off
Enlarged area of Photo #94, Long Meadow near Sunrise High Sierra Camp. Substantial tree die-off is visible across the entire southern exposure of the valley.

Changes in growth patterns of trees on domes and rocky slopes

Tree growth on domes and small patches of forest on rocky slopes has increased, including evidence of tree growth where semi-permanent snow patches once existed (Figure 17). Forty-nine photo sets contained domes and/or small patches of trees on rocky slopes, though only 69 percent (34) could be compared to c1985 photos (Table 7). Of this subset, 76 percent (26 sites) exhibited evidence of increased density and individual tree growth while 24 percent (8 sites) had no detectable change. In some cases, mature individuals were visible in the 2008 photos where sapling had previously been visible in the c1985 photos (Figure 19). In these instances, minimal or no new sapling growth was apparent, only additional growth of already germinated individuals.

As with larger forest stands, tree growth on rocky slopes and on and around domes has increased dramatically over the last century (Figure 20). In historic photographs, widely spaced individual trees and clearings between trees are visible. In the 2008 photo set, there is a visible increase of individual trees on and around domes, a reduction of forest clearings/space between trees, and evidence of new sapling growth (in some cases). Additionally, there are instances of new sapling and tree growth in areas previously containing summer snow patches (Figure 17). Evidence of mixed age stands suggests multiple cycles of germination which confirms Vale's (1987) conclusions. Decreased forest clearings and increased forest patches result in crowded forest stands, higher instances of disease/pest infestation, reduced forest biodiversity, and greater susceptibility to more intense fires (Peterson 1990; Ferrell 1996; Fites-Kaufman *et al.* 2007).

Domes and rocky hillsides provide interesting examples where individual trees can be identified and monitored remotely (Figure 21). Future study utilizing this repeat-photography data set could include monitoring of growth rates, as well as possible geologic changes surrounding instances of rock fall. Meadow, dome, and forest stand margins along with new growth into snow patches (see Millar *et al.* 2004) could also be studied using the historic reach available with this data set. Domes and rocky slopes, usually sparsely populated by individual trees, provide examples where individual trees could be monitored and tracked with future monitoring.

Table 7. Domes and Rocky Slope Photo Analysis
Repeat-photography analysis of photo sets where domes and rocky slopes were present. Photos compared c1985 and 2008 unless only c1900 photo available or otherwise noted. Visual change between photograph pairs identified as increase ("+"), decrease ("-"), no change ("/"), or not visible/not applicable ("nv").

Photo #	Area	Elevation (m)	Only c1900 photo available	Dome/rock slope visible	Density/ Cover (+, -, /)	Saplings visible
1	Tioga Pass	2985	x	y	+	nv
2	Tioga Pass	2953		y	+	y
3	Tioga Pass	3009		y	+	y
4	Tioga Pass	3024		y	+	y
5	Tioga Pass	2976		y	+	y
24	Tuolumne Meadows	2854		y	+	y
25	Tuolumne Meadows	2858	x	y	+	y
27	Tuolumne Meadows	2636		y	+	y
28	Pothole Dome	2622		y	+	y
29	Pothole Dome	2616		y	+	y
30	Pothole Dome	2621		y	+	y
31	Pothole Dome	2634		y	+	n
32	Tioga Road	2776	x	y	+	y
33	Tioga Road	2776		y	+	n
34	Tioga Road	2778	x	y	+	y
35	Tioga Road	2784	x	y	+	y
38	Glen Aulin	2663	x	y	+	y
40	Glen Aulin	2663	x	y	+	y
41	Glen Aulin	2663	x	y	+	y
44	Cathedral Lake	2990	x	y	/	n
45	Tenaya Lake	2533	x	y	+	y
46	Tenaya Lake	2535		y	+	y
47	Tenaya Lake	2489	x	y	+	y
48	Tenaya Lake	2493		y	/	nv
49	May Lake	2807		y	+	y
50	May Lake	3308		y	+	y
51	Cathedral Lake	2918		y	+	y
52	Cathedral Lake	2933		y	/	nv
54	Elizabeth Lake	2898		y	+	y
57	Vogelsang	3152	x	y	+	y
58	Vogelsang	3158	x	y	+	y
59	Vogelsang	3097		y	+	y
60	Vogelsang	3361	x	y	+	y
61	Vogelsang	2856		y	+	n
62	Tuolumne Meadows	2609		y	/	nv
63	Pothole Dome	2621		y	+	y
64	Tioga Road	2655		y	+	y
65	Tioga Road	2644		y	/	n
72	Glen Aulin	2591		y	+	n
75	Tenaya Lake	2594		y	/	y
76	Tenaya Lake	2618		y	/	n
79	May Lake	2855		y	/	n
81	Tenaya Lake	2503		y	/	n
82	Glen Aulin	2502		y	+	y
83	Cathedral Lake	2906		y	+	y
85	Glen Aulin	2597		y	+	n
90	Young Lakes	2691		y	+	y
96	Tenaya Lake	2566		y	nv	nv
98	Tenaya Lake	2488		y	+	y

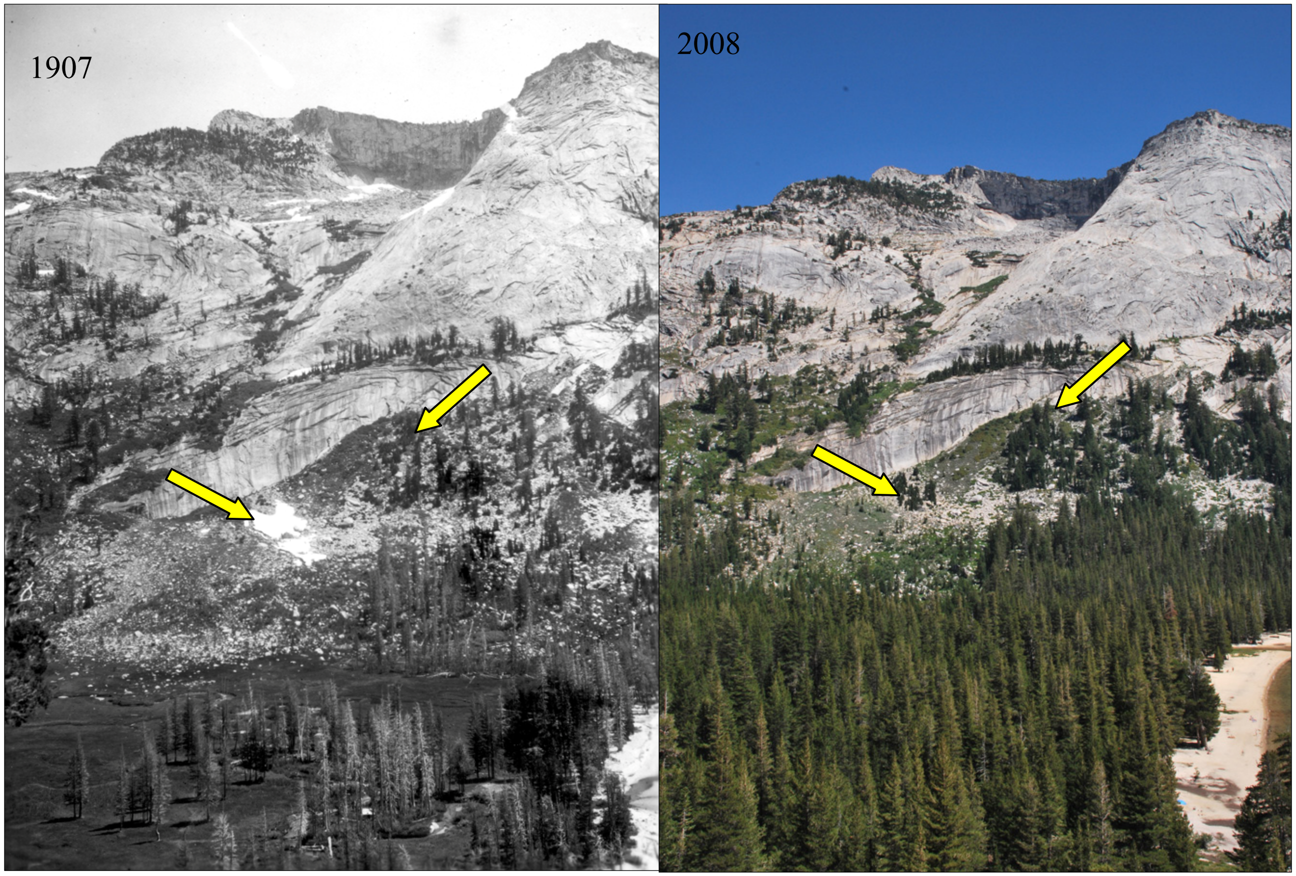


Figure 18. Results - Tree growth in snow patches and on rocky slopes
Photo # 45, the eastern shore of Tenaya Lake. Tree growth has increased on rocky slopes (at photo right) and in areas previously containing snow patches. These snowy areas would provide increased moisture through the summer months (at photo left). This image also includes a good comparison of tree invasion into meadows (at lower left). No photograph from c1985 is available for this site.

Figure 19. Results - No new saplings visible around domes
Photo # 29, at the western end of Tuolumne Meadows looking at Pothole Dome, where no new sapling growth is visible in 2008 along dome apron.

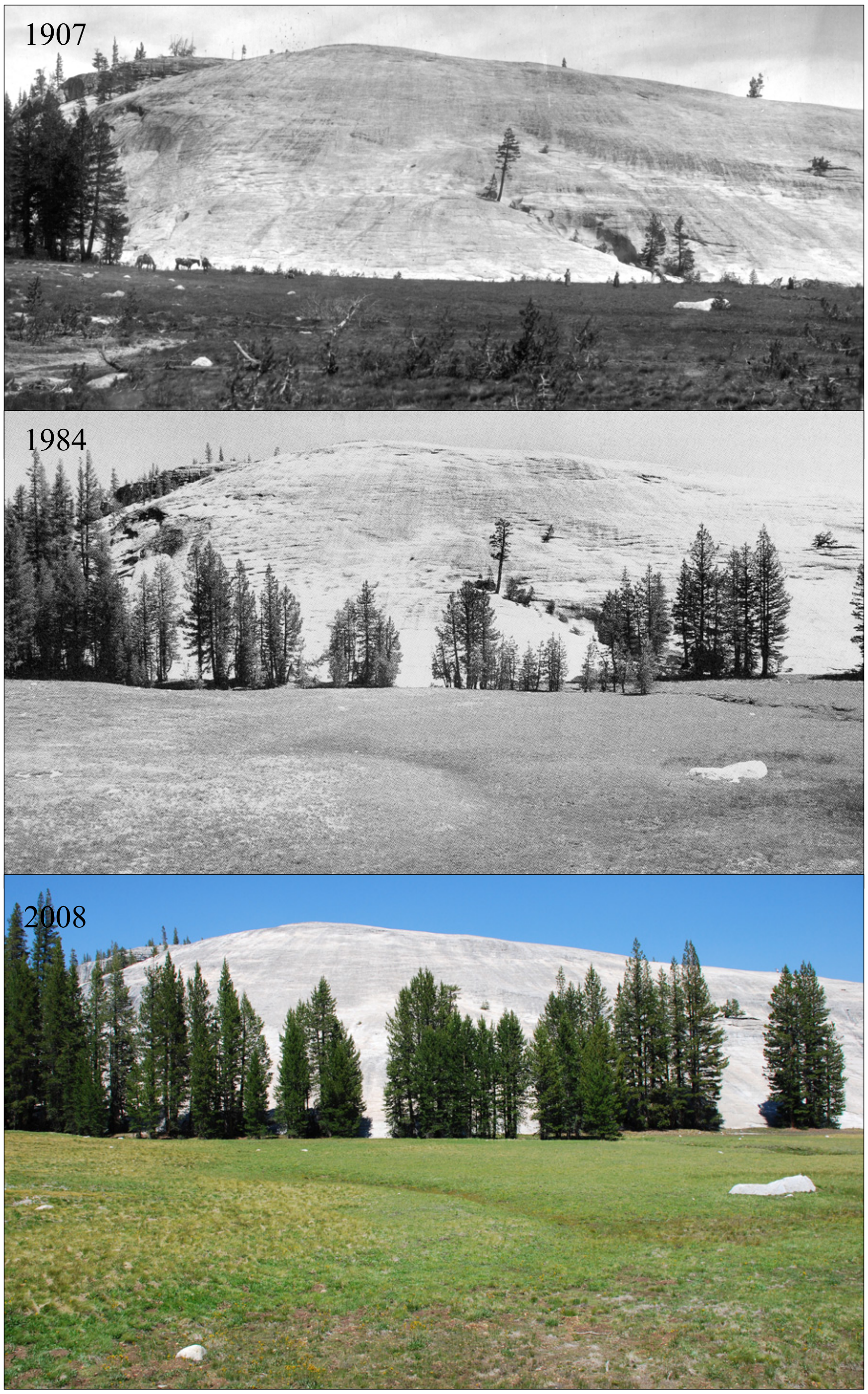


Figure 20. Results - Growth on rocky slopes
Photo #54, rocky hillside growth west of Elizabeth Lake at 2,898m. Note the additional growth and presence of new saplings amongst the protected rocks but not in the avalanche chute.

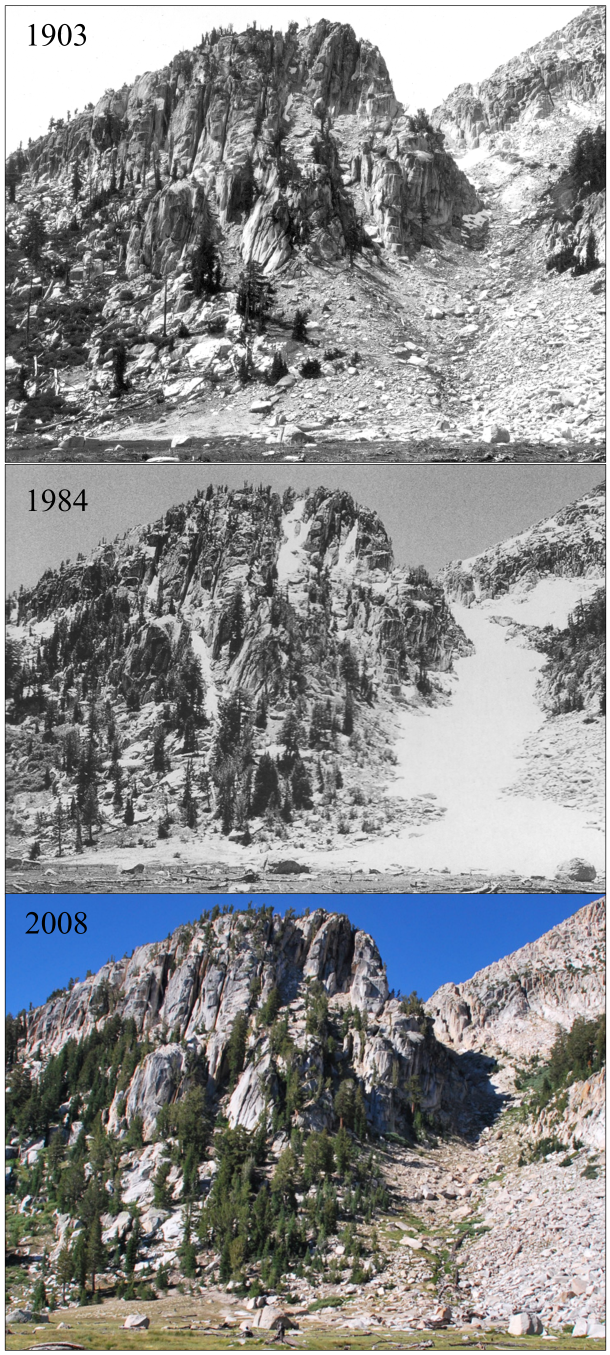
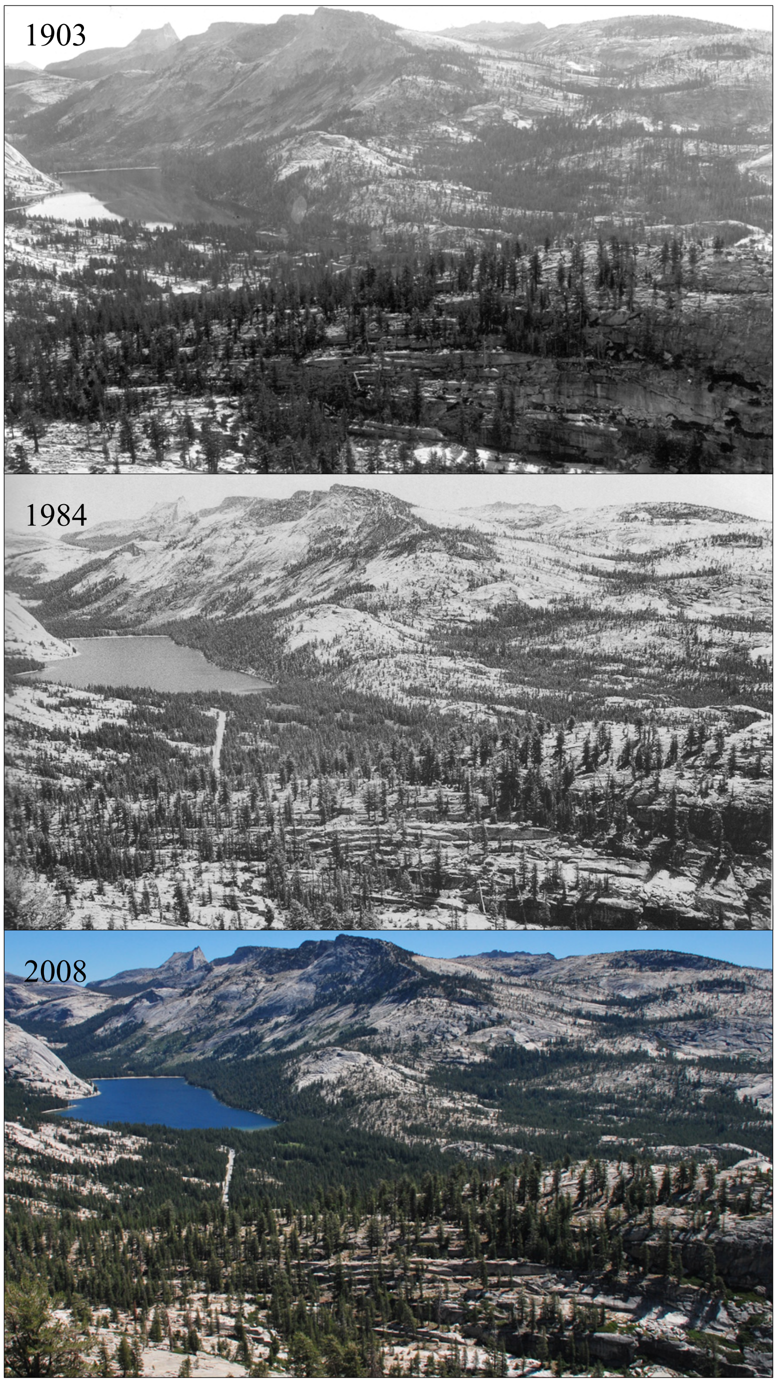


Figure 21. Results - Tree growth on granite domes
Photo #49, looking east from near the base of Mt. Hoffmann, towards Tenaya Lake. The foreground dome section and forest stand extending beyond provide examples of increased tree growth, the establishment of new saplings over time, and increased forest stand density.



Reduction of snow patches

Snow patches at higher elevations, visible during the summer time, were visible at many photo sites (Figure 21). Over 90 percent of photos that contained snow patches showed evidence of reduction (Table 8). In only two photo sets (#71 and 78), no detectable change in the size of patches was evident.

It is important to note that no conclusions are possible from this data set. While we know historic photographs were captured in the summer months, the exact dates of the c1900 and c1985 photographs are unknown. That said, even if we knew these dates it is near impossible to draw concrete conclusions from the visual record. There are few permanent glaciers in this area of the Sierra Nevada, and thus single snapshots of snow patch area are insufficient to glean conclusions. Though most of the snow visible in the summer is left over from the previous winters snowpack, snow and hail fall in the upper Sierra Nevada year round.

Specific time and date meta-data was collected in this study and can and should be used in the future to address snow/precipitation measurements related study(s). Annual snow depths, annual and average temperature analysis, and visible records of snow patches could be combined to address climate change in the Sierra Nevada Mountains. The inclusion of snow related data in this study is meant to prompt further investigation and use of the data set.

Table 8. Snow Patch Photo Analysis
Repeat-photography analysis of photo sets containing snow fields and patches. Photos compared c1985 and 2008 unless only c1900 photo available or otherwise noted. Visual change between photograph pairs identified as increase (“+”), decrease (“-”), no change (“/”), or not visible/not applicable (“nv”).

Photo #	Area	Elevation (m)	Only c1900 photo available	Snow patches (+, -, /)
1	Tioga Pass	2985	x	-
2	Tioga Pass	2953		-
3	Tioga Pass	3009		-
4	Tioga Pass	3024		-
5	Tioga Pass	2976		-
8	Tioga Pass	2992		-
9	Gaylor Lake	3257		-
10	Gaylor Lake	3257		-
11	Gaylor Lake	3257		-
12	Gaylor Lake	3257		-
13	Gaylor Lake	3257		-
14	Gaylor Lake	3257		-
17	Gaylor Lake	3257		-
18	Gaylor Lake	3257		-
19	Parker Pass	3393	x	-
20	Parker Pass	3462		-
28	Pothole Dome	2622		-
33	Tioga Road	2776		-
45	Tenaya Lake	2533	x	-
51	Cathedral Lake	2918		-
52	Cathedral Lake	2933		-
54	Elizabeth Lake	2898		-
57	Vogelsang	3152	x	-
58	Vogelsang	3158	x	-
59	Vogelsang	3097		-
60	Vogelsang	3361	x	-
66	May Lake	2746		-
71	Parker Pass	3324		/
78	Tuolumne Meadows	2614		/
90	Young Lakes	2691		-
97	Tioga Pass RS	3030		-

Figure 22. Results - Reduced snow fields
Photo #20, the Parker Pass saddle looking south at Kuna Crest. Note that the exact date of the 1903 and 1984 photos are not available. The 2008 photo was taken July 14th, 2008 at 11:41am.

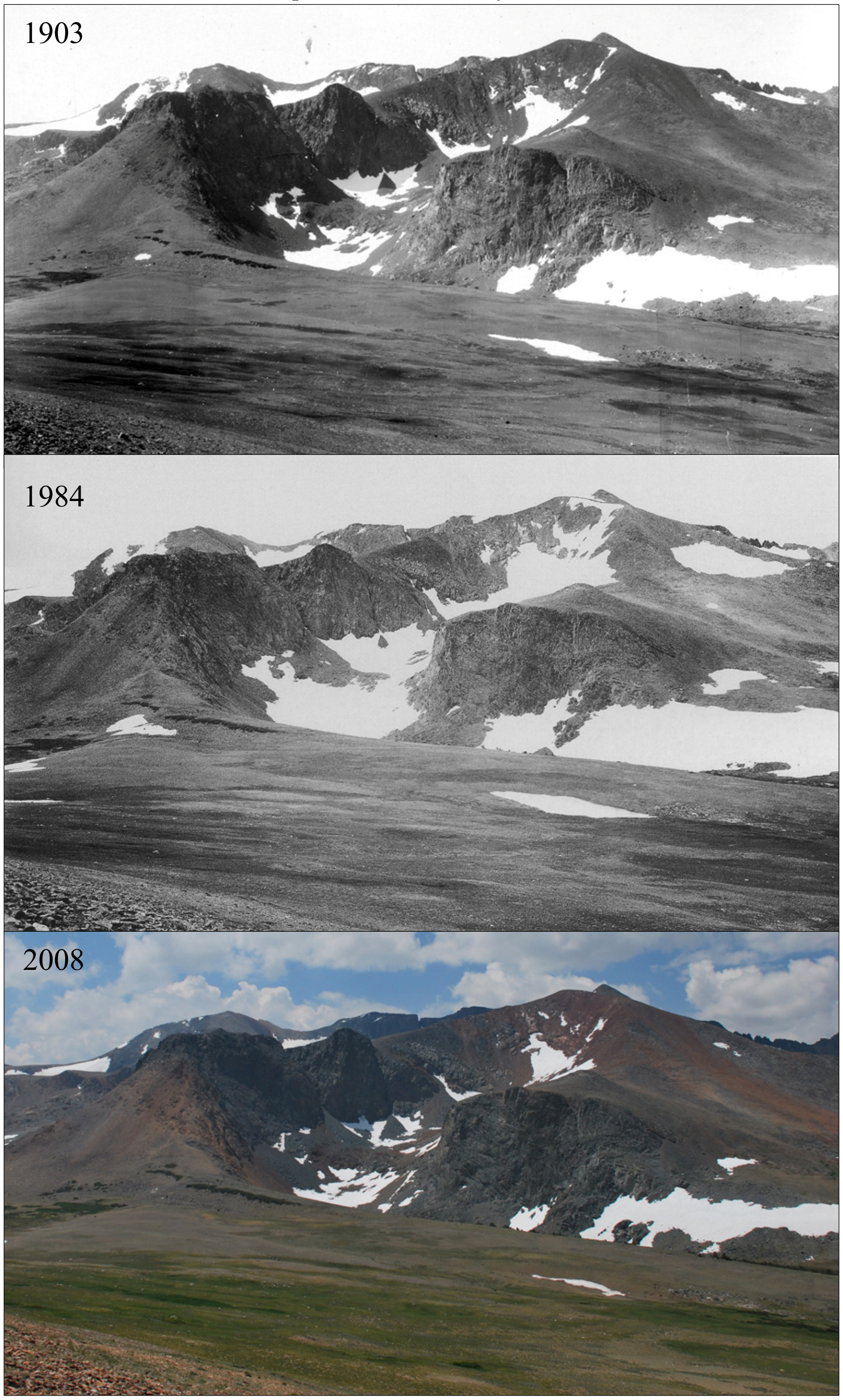
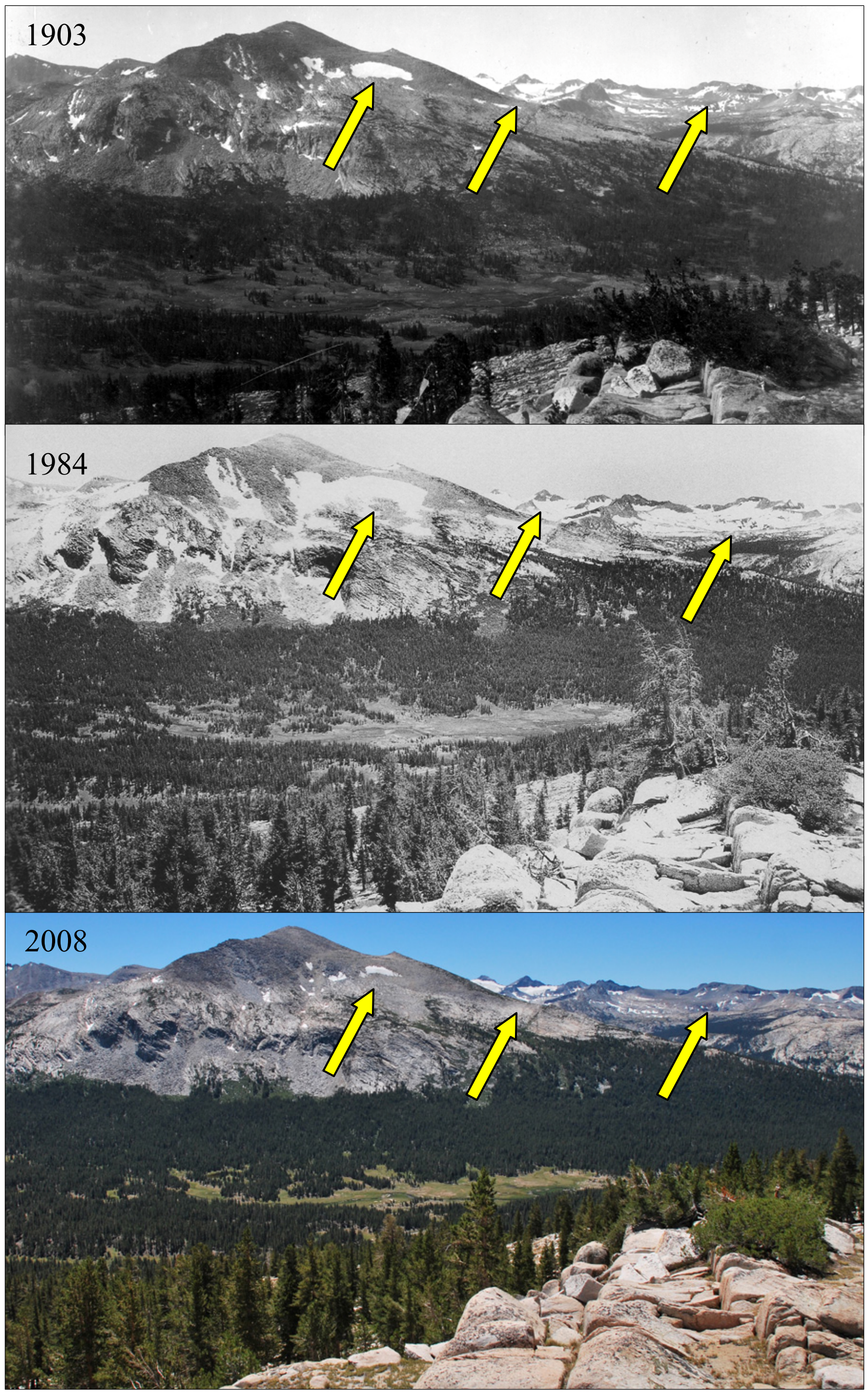


Figure 23. Results - Reduced snow fields II
Photo #13, a view south across lower Dana Meadow and Mammoth Peak captured on August 2nd. Summer snow patches can be seen on northern facing slopes of the surrounding peaks. The exact date for 1903 and 1984 photos was unavailable. The 2008 photo was taken August 2nd, 2008 at 12:10pm.



CONCLUSIONS

Detecting vegetation change over time periods beyond seasons and decades is an important component to our collective understanding of vegetation dynamics in upper elevation systems. Anthropogenic and natural drivers act upon mountain communities at varying temporal scales and thus it behooves us to continually refine and test detection methodologies and hypotheses of interaction.

Through visual interpretation of change from repeat-photography triplets, five vegetation change trends were identified in and around the Tuolumne Meadows area. By comparing historic photos (c1900 and c1985) to photos captured in 2008, the following five trends were detected: 1) Krummholz stands beyond the tree line exhibited increases in individual height (67%) and stand density (55%); 2) Within forest stands at the tree line, stand density and coverage increased (90%) and there was a noticeable upslope movement of the tree line from c1900 to 2008 (75%); 3) There was evidence of meadow invasion by trees (63%), in some cases substantial new growth; 4) Large stands of forest in the sub-alpine vegetation zone showed evidence of decreased forest clearings and increased stand density (63%); 5) On and around domes and on rocky slopes, the number of individuals as well as the health and density of branches of individual trees has increased (76%). Additionally, areas of large-scale tree die-off were identified (7%).

An increase in height and density of Krummholz formations suggests changes in weather patterns and climate shifts though the sample size of photo triplets were small. The growth visible within this data set mirrors Krummholz response to increased annual average temperature changes and a lengthening of the growing season (Hättenschwiler and Körner 1995; Grace *et al.* 2002; Roush *et al.* 2007; Beckage *et al.* 2008). Growth of trees at upper elevations is primarily restricted or encouraged by temperature and precipitation and thus future monitoring of vegetation growth and climate conditions in these areas is encouraged.

In and around the Tuolumne Meadows area, tree invasion into meadows was apparent and visibly substantial in 63 percent of the photo triplets studied. Previous studies have noted that the combination or interaction of cyclical precipitation increases and/or the removal of intensive livestock grazing in subalpine meadows as the cause(s) of noted tree invasion. Cyclical multi-year increases in precipitation have resulted in punctuated tree growth, particularly at meadow edges over the last century (Vale 1987). These periods of intense tree growth and establishment of new saplings was previously not possible when large herds of domestic grazers were a presence on the landscape. Livestock grazing was removed from meadows in the National Park in the 1920's and many attribute the advance of the treeline in the later 20th century into these meadows as a direct result (Franklin *et al.* 1971; Dunwiddie 1977; Bahre and Bradbury 1978; Vankat and Major 1978; Vale 1987; Taylor 1990; Miller and Halpern 1998). This study identified areas of tree invasion and suggests further research of local history and conditions is necessary to conclude causality of local tree invasion.

Across the study area forest stand density at the treeline and meadow edges, as well as on domes and rocky slopes, was seen to have increased while forest clearings have been reduced. Recent studies attribute forest stand density increases to a combination of reduced cyclical fire patterns, a history of logging and human influence on the landscape, and precipitation and temperature increase trends. In the study area it has been the policy of the National Park Service to suppress fires since the turn of the century through the 1970's and 80's. Sub-alpine landscapes void of fire returns result in a denser forest, reduced species diversity and increased stand homogeneity, increased susceptibility to pests and disease, and increased probability of larger, more widespread, and more intense fires.

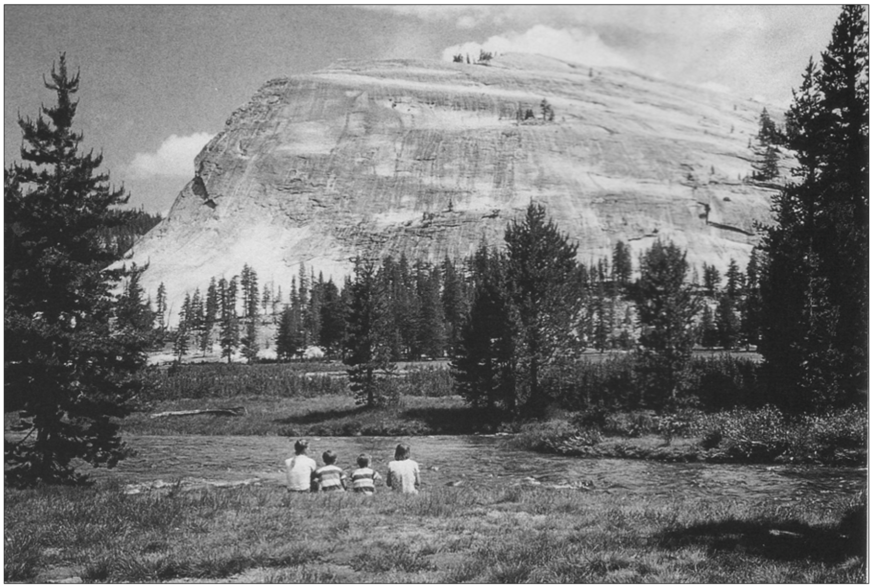
In the mid 1980's, Vale (1987) found that while there was clear evidence of increased forest stand density, invasion of trees into meadows, increased Krummholz formation growth, and increased density of forest patches over the previous ~80 years, he found no conclusive evidence of upslope treeline movement. The results of this study conclude that there has been an upslope growth trend at the treeline over the last century visible from the photo sets. This departure from Vale (1987) mirrors findings of similar studies of the last two decades across the Sierra Nevada and American West and is likely considering the qualitative nature of photo-analysis. Repeat-photography analysis can vary based on the judgment and experience of the reviewer(s). Vale's findings and analysis were not available for each photo set and thus his summary results are the only permanent record of his original analysis. It is important that analysis of photos remain consistent across the entire data set and ideally repeat-photography review(s) should be conducted by the same person across all data. The inclusion of analysis results for each photo triplet from this study are meant to encourage further review with the hope that a marriage of qualitative/quantitative methods in the future could possibly reduce analysis inconsistencies and increase certainty of conclusions.

Repeat-photography has become less expensive and more easily repeatable as digital technologies have expanded. In Yosemite and the Central Sierra Nevada, repeat analysis and long term monitoring are necessary and indispensible tools to resource and conservation managers. The methods discussed and utilized, along with project results will provide the basis for continued monitoring of alpine and sub-alpine forest systems in Central Sierra Nevada Range. Armed with over 100 years of qualitative data, future monitoring projects could and should utilize the photographic sites located in this study. By expanding the meta-data available for each photo site, including date, time, Lat/Long location, and optics specific data, precise data collection can continue into the future. The addition of snow patch and large scale forest die-offs visible in this photo set could be included in future monitoring of the area.

Questions remains whether species found in upper elevation systems can/will keep pace with rapid anthropogenic and natural driven changes (Bartlein 1997; Hansen *et al.* 2001). Will mountain tops indeed become quickly disappearing ‘islands’ for terrestrial vegetation? What will the long term effects of current and future climate cycling, pest/disease prevalence, and fire cycling have on upper elevation systems? Development of future vegetation management policies depends on continued monitoring of meadows, tree lines, and forest stands.

It is hoped that increased accuracy of repeat-photography sites, made available through this project, would aid additional research in this region. Examples of possible tangential studies include post fire succession monitoring, alpine glacier and snowpack studies, sequential ground truthing for aerial and remote sensing projects, and forest and meadow dynamics investigations. Future projects could utilize the photograph triplets from this study to their own ends.

International consensus suggests rapid climate change in the coming century, especially in mountain systems (IPCC 2007). The integration of change detection methods, both quantitative and qualitative, is necessary if our knowledge of fragile mountain systems is to expand (Marston 2008). Monitoring systems must be in place to expand the temporal scale of study to cover future affects of climate change and/or unknown/unpredictable disturbance events. Repeat-photography has the potential to fill many gaps left vacant in change detection methodologies. True long term monitoring of vegetation at upper elevations of the Sierra Nevada will require decades and centuries of further study.



T. Vale & family,
on the banks of the Tuolumne River across
from Lembert Dome, c1985.

N.Wasserman, August 2008

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Appendix A. Repeat-photography site locations

Appendix A. Repeat-photography site locations

Photo #	Label	Area	Latitude	Longitude	Elevation (m)	GPS Accuracy (m)	Direction (east=0°)	Date	Time
1	1-V01-US3142	Tioga Pass	N37°56.271'	W119°14.006'	2985	10	270	8/2/2008	9:15am
2	2-V02-US3119	Tioga Pass	N37°56.280'	W119°14.104'	2953	6	260°	8/2/2008	9am
3	3-V03-US3137	Tioga Pass	N37°55.815'	W119°14.691'	3009	10	160	7/12/2008	10:50am
4	4-V04-US3135	Tioga Pass	N37°55.601'	W119°14.761'	3024	5	170	7/12/2008	11:15am
5	5-V05-US3131	Tioga Pass	N37°55.108'	W119°15.308'	2976	4	330	7/12/2008	11:45am
8	8-V08-US3116	Tioga Pass	N37°53.787'	W119°15.389'	2992	10	0	8/2/2008	2:30pm
9	9-V09-US2129	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	80	8/2/2008	12:10pm
10	10-V10-US2120	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	30°	8/2/2008	12:10pm
11	11-V11-US2121	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	10	8/2/2008	12:10pm
12	12-V12-US2122	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	300	8/2/2008	12:10pm
13	13-V13-US2123	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	270	8/2/2008	12:10pm
14	14-V14-US2124	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	230	8/2/2008	12:10pm
15	15-V15-US2125	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	210	8/2/2008	12:10pm
16	16-V16-US2126	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	190	8/2/2008	12:10pm
17	17-V17-US2127	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	130	8/2/2008	12:10pm
18	18-V18-US2128	Gaylor Lake	N37°53.843'	W119°16.467'	3257	3	0	8/2/2008	12:10pm
19	19-V19-US2092	Parker Pass	N37°50.423'	W119°12.369'	3393	3	340	7/14/2008	12:00pm
20	20-V20-US2094	Parker Pass	N37°50.723'	W119°12.520'	3462	6	290	7/14/2008	11:41am
22	22-V22-US2098	Lyell Canyon	N37°50.573'	W119°17.163'	2687	10	280	8/9/2008	12:30pm
24	24-V24-US2164	Tuolumne Meadows	N37°53.031'	W119°20.713'	2854	3	210°	8/10/2008	2:20pm
25	25-V25-US2165	Tuolumne Meadows	N37°52.953'	W119°20.738'	2858	3	240°	8/10/2008	2:30pm
26	26-V26-US3111	Tuolumne Meadows	N37°52.717'	W119°21.798'	2627	6	20	8/8/2008	3pm
27	27-V27-US2155	Tuolumne Meadows	N37°52.418'	W119°22.885'	2636	2	180	7/26/2008	2pm
28	28-V28-US3105	Pothole Dome	N37°52.614'	W119°23.687'	2622	7	30°	7/26/2008	2:15pm
29	29-V29-US3123	Pothole Dome	N37°52.653'	W119°23.711'	2616	11	170	7/10/2008	10:10am
30	30-V30-US2037	Pothole Dome	N37°52.641'	W119°23.558'	2621	3	195°	7/10/2008	11:10am
31	31-V31-US3127	Pothole Dome	N37°52.708'	W119°23.680'	2634	3	300	7/10/2008	10:50am
32	32-V32-US2135	Tioga Road	N37°53.104'	W119°24.337'	2776	2	320	8/3/2008	2:15pm
33	33-V33-US2136	Tioga Road	N37°53.113'	W119°24.331'	2776	3	10	8/3/2008	2:45pm
34	34-V34-US2137	Tioga Road	N37°53.119'	W119°24.361'	2778	2	320°	8/3/2008	2:30pm
35	35-V35-US2138	Tioga Road	N37°53.122'	W119°24.380'	2784	2	100	8/3/2008	2:30pm
36	36-V36-US0782a	Tuolumne Meadows	N37°53.053'	W119°22.702'	2619	6	200°	8/8/2008	1pm
38	38-V37-US2133-LOWER	Glen Aulin	N37°54.413'	W119°25.846'	2663	9	30	7/27/2008	9:10am
40	40-V38-US2132	Glen Aulin	N37°54.413'	W119°25.846'	2663	9	70	7/27/2008	9:10am
41	41-V39-US2131	Glen Aulin	N37°54.413'	W119°25.846'	2663	9	80	7/27/2008	9:10am
42	42-V40-US2160	Young Lakes	N37°53.894'	W119°22.980'	2729	8	270°	8/8/2008	1:20pm
44	44-V42-US2157	Cathedral Lake	N37°51.691'	W119°25.169'	2990	5	30°	8/3/2008	12:30pm
45	45-V43-US3141	Tenaya Lake	N37°50.258'	W119°27.294'	2533	-	0	8/1/2008	2:45pm
46	46-V44-US3118	Tenaya Lake	N37°50.169'	W119°27.402'	2535	8	10	8/1/2008	2:30pm
47	47-V45-US2189	Tenaya Lake	N37°49.723'	W119°28.053'	2489	5	40	8/1/2008	2:10pm
48	48-VBK-77	Tenaya Lake	N37°49.650'	W119°28.051'	2493	6	100	8/1/2008	1pm
49	49-V47-US2188	May Lake	N37°49.219'	W119°29.376'	2807	3	40°	8/4/2008	11:45am

Appendix A Repeat-photography site locations (cont.)

Photo #	Label	Area	Latitude	Longitude	Elevation (m)	GPS Accuracy (m)	Direction (east=0°)	Date	Time
50	50-V48-US3161	May Lake	N37°50.817'	W119°30.637'	3308	4	190	8/4/2008	9:45pm
51	51-V49-US2073A	Cathedral Lake	N37°50.565'	W119°25.038'	2918	4	180	8/3/2008	10am
52	52-V50-US2202	Cathedral Lake	N37°50.417'	W119°24.970'	2933	7	270	8/3/2008	10:30am
54	54-V52-US2063	Elizabeth Lake	N37°50.809'	W119°22.348'	2898	7	210°	8/9/2008	9:30am
56	56-V54-US2059	Vogelsang	N37°48.472'	W119°19.596'	3152	4	20°	7/25/2008	11:32am
57	57-V55-US2058	Vogelsang	N37°48.476'	W119°19.593'	3152	3	240°	7/25/2008	11:20am
58	58-V56-US2067	Vogelsang	N37°48.240'	W119°20.894'	3158	6	210°	7/25/2008	2:50pm
59	59-V57-US2069	Vogelsang	N37°47.811'	W119°20.639'	3097	4	300	7/25/2008	10:23am
60	60-V58-US2080	Vogelsang	N37°47.645'	W119°19.197'	3361	3	170	7/25/2008	12:50pm
61	61-V59-US2177	Vogelsang	N37°46.774'	W119°22.882'	2856	10	260	7/25/2008	9am
62	62-VBK-01	Tuolumne Meadows	N37°53.037'	W119°22.758'	2609	9	210°	8/8/2008	12:30pm
63	63-VBK-03	Pothole Dome	N37°52.619'	W119°23.680'	2621	3	120	7/10/2008	10am
64	64-VBK-04	Tioga Road	N37°52.708'	W119°24.729'	2655	7	230°	8/1/2008	4:30pm
65	65-VBK-06	Tioga Road	N37°51.821'	W119°26.034'	2644	4	290	8/1/2008	3:30pm
66	66-VBK-07	May Lake	N37°49.338'	W119°29.462'	2746	6	90	8/4/2008	12pm
67	67-VBK-09	Tuolumne Meadows	N37°52.757'	W119°21.306'	2625	2	210°	8/10/2008	3:11pm
68	68-VBK-10	Parker Pass	N37°52.184'	W119°14.298'	3023	10	110	7/14/2008	1:50pm
71	71-VBK-15	Parker Pass	N37°50.807'	W119°13.112'	3324	7	280	7/14/2008	11:05am
72	72-VBK-18	Glen Aulin	N37°53.792'	W119°24.264'	2591	3	130	7/26/2008	4pm
74	74-VBK-21B	Tenaya Lake	N37°48.940'	W119°29.332'	2588	6	20	8/1/2008	11:50am
75	75-VBK-21C	Tenaya Lake	N37°48.943'	W119°29.343'	2594	3	20	8/1/2008	11:50am
76	76-VBK-21D	Tenaya Lake	N37°48.912'	W119°29.281'	2618	16	20	8/1/2008	11:50am
78	78-VBK-23	Tuolumne Meadows	N37°53.181'	W119°23.180'	2614	4	270	8/8/2008	2pm
79	79-VBK-26	May Lake	N37°50.709'	W119°29.483'	2855	18	180	8/4/2008	8:30am
81	81-VBK-29	Tenaya Lake	N37°49.616'	W119°28.336'	2503	2	90	8/1/2008	1:30pm
82	82-VBK-32	Glen Aulin	N37°54.240'	W119°24.929'	2502	5	130	7/27/2008	10:40am
83	83-VBK-38	Cathedral Lake	N37°50.695'	W119°24.762'	2906	6	80	8/3/2008	11:00am
85	85-VBK-41	Glen Aulin	N37°53.361'	W119°23.409'	2597	7	90	7/26/2008	3:20pm
89	89-VBK-57	Mono Pass	N37°56.283'	W119°15.610'	2982	7	300	8/2/2008	10:30am
90	90-VBK-60	Young Lakes	N37°53.836'	W119°22.930'	2691	5	270	8/8/2008	1:25pm
91	91-VBK-62	Tioga Pass	N37°56.950'	W119°13.474'	2779	12	70	8/2/2008	8:50am
92	92-VBK-63	Tuolumne Meadows	N37°52.721'	W119°22.005'	2621	7	300	8/8/2008	11:45am
93	93-VBK-65	Tenaya Lake	N37°50.091'	W119°27.086'	2491	4	110	8/1/2008	2:45pm
94	94-VBK-66	Sunrise	N37°47.558'	W119°25.680'	2860	4	90	8/10/2008	10:50am
96	96-VBK-72A	Tenaya Lake	N37°48.728'	W119°29.013'	2566	3	70	8/1/2008	12:30pm
97	97-VBK-73	Tioga Pass RS	N37°54.677'	W119°15.481'	3030	-	230	8/2/2008	11:00am
98	98-VBK-74	Tenaya Lake	N37°50.180'	W119°27.193'	2488	8	170	8/1/2008	3:15pm
99	99-VBK-75	Tenaya Lake	N37°49.562'	W119°28.075'	2529	20	30	8/1/2008	12:50pm
100	100-VBK-76	Tenaya Lake	N37°49.649'	W119°28.049'	2488	6	200	8/1/2008	1pm
101	101-VBK-78	Tenaya Lake	N37°49.657'	W119°28.085'	2495	4	300	8/1/2008	1:15pm
102	102-VBK-79	Tenaya Lake	N37°49.650'	W119°28.091'	2495	5	60°	8/1/2008	1:25pm

Appendix B. 2008 photograph and camera meta-data

All 2008 photographs were captured with a Nikon D60 DSLR and Nikon Nikkor 18-135mm (f/3.5-5.6G) DX lens in JPEG format (RBG, 3872x2592px, 300ppi).

Appendix B. 2008 photograph and camera meta-data

Photo #	Label	Area	*f* / stop	Shutter Speed	Focal length (35mm equivalent)	ISO
1	1-V01-US3142	Tioga Pass	5.6	1/500	30mm	200
2	2-V02-US3119	Tioga Pass	5.6	1/1250	27mm	200
3	3-V03-US3137	Tioga Pass	5.6	1/1000	39mm	200
4	4-V04-US3135	Tioga Pass	13.0	1/200	27mm	200
5	5-V05-US3131	Tioga Pass	5.6	1/1000	33mm	200
8	8-V08-US3116	Tioga Pass	5.6	1/500	27mm	200
9	9-V09-US2129	Gaylor Lake	5.6	1/1600	33mm	200
10	10-V10-US2120	Gaylor Lake	5.6	1/1250	30mm	200
11	11-V11-US2121	Gaylor Lake	5.6	1/800	27mm	200
12	12-V12-US2122	Gaylor Lake	5.6	1/1250	27mm	200
13	13-V13-US2123	Gaylor Lake	5.6	1/1250	30mm	200
14	14-V14-US2124	Gaylor Lake	5.6	1/1000	30mm	200
15	15-V15-US2125	Gaylor Lake	5.6	1/1250	36mm	200
16	16-V16-US2126	Gaylor Lake	18.0	1/100	30mm	200
17	17-V17-US2127	Gaylor Lake	5.6	1/2500	30mm	200
18	18-V18-US2128	Gaylor Lake	5.6	1/3200	33mm	200
19	19-V19-US2092	Parker Pass	5.6	1/1250	36mm	200
20	20-V20-US2094	Parker Pass	5.6	1/3200	30mm	200
22	22-V22-US2098	Lyell Canyon	5.6	1/1250	36mm	200
24	24-V24-US2164	Tuolumne Meadows	5.6	1/640	30mm	200
25	25-V25-US2165	Tuolumne Meadows	5.6	1/640	27mm	200
26	26-V26-US3111	Tuolumne Meadows	5.6	1/500	27mm	200
27	27-V27-US2155	Tuolumne Meadows	5.6	1/640	33mm	200
28	28-V28-US3105	Pothole Dome	5.6	1/640	42mm	200
29	29-V29-US3123	Pothole Dome	5.6	1/640	30mm	200
30	30-V30-US2037	Pothole Dome	5.6	1/1000	39mm	200
31	31-V31-US3127	Pothole Dome	5.6	1/640	33mm	200
32	32-V32-US2135	Tioga Road	5.6	1/1250	27mm	200
33	33-V33-US2136	Tioga Road	5.6	1/2500	27mm	200
34	34-V34-US2137	Tioga Road	5.6	1/1600	33mm	200
35	35-V35-US2138	Tioga Road	5.6	1/1600	30mm	200
36	36-V36-US0782a	Tuolumne Meadows	5.6	1/800	27mm	200
38	38-V37-US2133-LOWER	Glen Aulin	5.6	1/2000	33mm	200
40	40-V38-US2132	Glen Aulin	5.6	1/4000	33mm	200
41	41-V39-US2131	Glen Aulin	18.0	1/125	33mm	200
42	42-V40-US2160	Young Lakes	5.6	1/200	27mm	200
44	44-V42-US2157	Cathedral Lake	5.6	1/1000	27mm	200
45	45-V43-US3141	Tenaya Lake	18.0	1/80	36mm	200
46	46-V44-US3118	Tenaya Lake	5.6	1/1600	36mm	200
47	47-V45-US2189	Tenaya Lake	18.0	1/100	33mm	200
48	48-VBK-77	Tenaya Lake	5.6	1/640	30mm	200
49	49-V47-US2188	May Lake	5.6	1/1250	27mm	200

Appendix B. 2008 photograph and camera meta-data (cont.)

Photo #	Label	Area	*f* / stop	Shutter Speed	Focal length (35mm equivalent)	ISO
50	50-V48-US3161	May Lake	5.6	1/3200	33mm	200
51	51-V49-US2073A	Cathedral Lake	5.6	1/400	30mm	200
52	52-V50-US2202	Cathedral Lake	5.6	1/640	33mm	200
54	54-V52-US2063	Elizabeth Lake	5.6	1/800	27mm	200
56	56-V54-US2059	Vogelsang	5.6	1/640	39mm	200
57	57-V55-US2058	Vogelsang	5.6	1/800	39mm	200
58	58-V56-US2067	Vogelsang	5.6	1/1250	46mm	200
59	59-V57-US2069	Vogelsang	5.6	1/640	33mm	200
60	60-V58-US2080	Vogelsang	5.6	1/1250	36mm	200
61	61-V59-US2177	Vogelsang	5.6	1/640	42mm	200
62	62-VBK-01	Tuolumne Meadows	5.6	1/1000	27mm	200
63	63-VBK-03	Pothole Dome	5.6	1/800	36mm	200
64	64-VBK-04	Tioga Road	5.6	1/1000	36mm	200
65	65-VBK-06	Tioga Road	5.6	1/1250	36mm	200
66	66-VBK-07	May Lake	5.6	1/2000	33mm	200
67	67-VBK-09	Tuolumne Meadows	5.6	1/800	39mm	200
68	68-VBK-10	Parker Pass	5.6	1/125	27mm	200
71	71-VBK-15	Parker Pass	5.6	1/1000	39mm	200
72	72-VBK-18	Glen Aulin	5.6	1/1600	39mm	200
74	74-VBK-21B	Tenaya Lake	5.6	1/500	27mm	200
75	75-VBK-21C	Tenaya Lake	5.6	1/500	27mm	200
76	76-VBK-21D	Tenaya Lake	5.6	1/320	42mm	200
78	78-VBK-23	Tuolumne Meadows	18.0	1/100	33mm	200
79	79-VBK-26	May Lake	5.6	1/2500	30mm	200
81	81-VBK-29	Tenaya Lake	5.6	1/1600	36mm	200
82	82-VBK-32	Glen Aulin	5.6	1/1000	46mm	200
83	83-VBK-38	Cathedral Lake	5.6	1/500	30mm	200
85	85-VBK-41	Glen Aulin	5.6	1/1000	27mm	200
89	89-VBK-57	Mono Pass	5.6	1/640	36mm	200
90	90-VBK-60	Young Lakes	18.0	1/100	27mm	200
91	91-VBK-62	Tioga Pass	5.6	1/400	30mm	200
92	92-VBK-63	Tuolumne Meadows	5.6	1/640	27mm	200
93	93-VBK-65	Tenaya Lake	5.6	1/800	27mm	200
94	94-VBK-66	Sunrise	5.6	1/400	27mm	200
96	96-VBK-72A	Tenaya Lake	5.6	1/1000	46mm	200
97	97-VBK-73	Tioga Pass RS	5.6	1/3200	36mm	200
98	98-VBK-74	Tenaya Lake	5.6	1/800	30mm	200
99	99-VBK-75	Tenaya Lake	5.6	1/500	33mm	200
100	100-VBK-76	Tenaya Lake	5.6	1/400	30mm	200
101	101-VBK-78	Tenaya Lake	5.6	1/1000	27mm	200
102	102-VBK-79	Tenaya Lake	5.6	1/1250	30mm	200

Appendix C. Historic photograph meta-data

In Table:

[1] Vale, T. (1987). "Vegetation Change and Park Purposes in the High Elevations of Yosemite National Park, California." Annals of the Association of American Geographers 77(1): p1-18.

[2] Vale, T. and G. Vale (1994). Time and the Tuolumne Landscape: Continuity and Change in the Yosemite High Country. Salt Lake City, UT, University of Utah Press.

[3] USGS (2007). "U.S. Geological Survey Photographic Library." Retrieved January,2008, from http://libraryphoto.dr.usgs.gov/.

Appendix C. Historic photograph meta-data

Photo #	Label	Vale (1987) ID[1]	Vale & Vale (1994) ID[2]	Vale Year	USGS ID[3]	USGS Photographer	USGS Year	USGS html
1	1-V01-US3142	01	-	-	3142	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/land/ggk03142.jpg
2	2-V02-US3119	02	69	1984	3119	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/port/ggk03119.jpg
3	3-V03-US3137	03	14	1984	3137	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/port/ggk03137.jpg
4	4-V04-US3135	04	70	1984	3135	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/port/ggk03135.jpg
5	5-V05-US3131	05	16	1984	3131	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/land/ggk03131.jpg
8	8-V08-US3116	08	58	1984	3116	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb053/port/ggk03116.jpg
9	9-V09-US2129	09	53	1984	2129	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02129.jpg
10	10-V10-US2120	10	54	1984	2120	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02120.jpg
11	11-V11-US2121	11	45	1984	2121	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02121.jpg
12	12-V12-US2122	12	46	1984	2122	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02122.jpg
13	13-V13-US2123	13	47	1984	2123	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02123.jpg
14	14-V14-US2124	14	48	1984	2124	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02124.jpg
15	15-V15-US2125	15	49	1984	2125	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02125.jpg
16	16-V16-US2126	16	50	1984	2126	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02126.jpg
17	17-V17-US2127	17	51	1984	2127	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02127.jpg
18	18-V18-US2128	18	52	1984	2128	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02128.jpg
19	19-V19-US2092	19	-	-	2092	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02092.jpg
20	20-V20-US2094	20	24	1984	2094	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02094.jpg
22	22-V22-US2098	22	59	1984	2098	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02098.jpg
24	24-V24-US2164	24	33	1984	2164	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb054/land/ggk02164.jpg
25	25-V25-US2165	25	-	-	2165	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb054/land/ggk02165.jpg
26	26-V26-US3111	26	64	1984	3111	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/port/ggk03111.jpg
27	27-V27-US2155	27	35	1984	2155	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb054/land/ggk02155.jpg
28	28-V28-US3105	28	56	1984	3105	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb022/land/ggk03105.jpg
29	29-V29-US3123	29	68	1984	3123	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb054/land/ggk03123.jpg
30	30-V30-US2037	30	30	1984	2037	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb022/land/ggk02037.jpg
31	31-V31-US3127	31	31	1984	3127	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/port/ggk03127.jpg
32	32-V32-US2135	32	-	-	2135	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02135.jpg
33	33-V33-US2136	33	67	1985	2136	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02136.jpg
34	34-V34-US2137	34	-	-	2137	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02137.jpg
35	35-V35-US2138	35	-	-	2138	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02138.jpg
36	36-V36-US0782a	36	-	-	0782	F.E. Matthes	1936	http://libraryphoto.cr.usgs.gov/htmlorg/lpb026/land/mfe00782.jpg
38	38-V37-US2133-LOWER	37	-	-	2133	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb199/land/ggk02133.jpg
40	40-V38-US2132	38	-	-	2132	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02132.jpg
41	41-V39-US2131	39	-	-	2131	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/land/ggk02131.jpg
42	42-V40-US2160	40	17	1985	2160	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb170/port/ggk02160.jpg
44	44-V42-US2157	42	-	-	2157	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb053/port/ggk02157.jpg
45	45-V43-US3141	43	-	-	3141	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb053/port/ggk03141.jpg
46	46-V44-US3118	44	20	1984	3118	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb054/land/ggk03118.jpg
47	47-V45-US2189	45	-	-	2189	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb170/land/ggk02189.jpg
48	48-VBK-77	46	77	1984	3151	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb054/land/ggk03151.jpg
49	49-V47-US2188	47	61	1984	2188	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb054/land/ggk02188.jpg

Appendix C. Historic photograph meta-data (cont.)

Photo #	Label	Vale (1987) ID[1]	Vale & Vale (1994) ID[2]	Vale Year	USGS ID[3]	USGS Photographer	USGS Year	USGS html
50	50-V48-US3161	48	27	1984	3161	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/port/ggk03161.jpg
51	51-V49-US2073A	49	2	1984	2073a	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb163/land/ggk2073a.jpg
52	52-V50-US2202	50	5	1984	2202	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb170/land/ggk02202.jpg
54	54-V52-US2063	52	37	1984	2063	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb163/port/ggk02063.jpg
56	56-V54-US2059	54	-	-	2059	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb001/land/ggk02059.jpg
57	57-V55-US2058	55	-	-	2058	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb163/port/ggk02058.jpg
58	58-V56-US2067	56	-	-	2067	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb163/land/ggk02067.jpg
59	59-V57-US2069	57	36	1984	2069	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb163/port/ggk02069.jpg
60	60-V58-US2080	58	-	-	2080	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb164/port/ggk02080.jpg
61	61-V59-US2177	59	12	1984	2177	G.K. Gilbert	1903	http://libraryphoto.cr.usgs.gov/htmlorg/lpb170/land/ggk02177.jpg
62	62-VBK-01	-	1	1989	140	R.B. Dole	1913	http://libraryphoto.cr.usgs.gov/htmlorg/lpb022/land/drb00140.jpg
63	63-VBK-03	-	3	1987	467	F.E. Matthes	1917	http://libraryphoto.cr.usgs.gov/htmlorg/lpb026/land/mfe00467.jpg
64	64-VBK-04	-	4	1987	-	F.C. Calkins	1913	
65	65-VBK-06	-	6	1987	339	F.C. Calkins	1913	http://libraryphoto.cr.usgs.gov/htmlorg/lpb018/land/cfc00339.jpg
66	66-VBK-07	-	7	1988	3160	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/land/ggk03160.jpg
67	67-VBK-09	-	9	1987	138	R.B. Dole	1913	http://libraryphoto.cr.usgs.gov/htmlorg/lpb022/land/drb00138.jpg
68	68-VBK-10	-	10	1988	-	F.E. Matthes	1917	
71	71-VBK-15	-	15	1988	-	F.E. Matthes	1917	
72	72-VBK-18	-	18	1987	-	F.C. Calkins	1913	
74	74-VBK-21B	-	21b	1988	354	F.E. Matthes	1917	http://libraryphoto.cr.usgs.gov/htmlorg/lpb025/land/mfe00354.jpg
75	75-VBK-21C	-	21c	1988	354	F.E. Matthes	1917	http://libraryphoto.cr.usgs.gov/htmlorg/lpb025/land/mfe00354.jpg
76	76-VBK-21D	-	21d	1988	354	F.E. Matthes	1917	http://libraryphoto.cr.usgs.gov/htmlorg/lpb025/land/mfe00354.jpg
78	78-VBK-23	-	23	1988	382	F.C. Calkins	1913	http://libraryphoto.cr.usgs.gov/htmlorg/lpb018/land/cfc00382.jpg
79	79-VBK-26	-	26	1988	-	F.E. Matthes	1914	
81	81-VBK-29	-	29	1988	346	F.E. Matthes	1917	http://libraryphoto.cr.usgs.gov/htmlorg/lpb025/land/mfe00346.jpg
82	82-VBK-32	-	32	1987	416	F.C. Calkins	1913	http://libraryphoto.cr.usgs.gov/htmlorg/lpb018/land/cfc00416.jpg
83	83-VBK-38	-	38	1987	368	F.C. Calkins	1913	http://libraryphoto.cr.usgs.gov/htmlorg/lpb018/land/cfc00368.jpg
85	85-VBK-41	-	41	1987	415	F.C. Calkins	1913	http://libraryphoto.cr.usgs.gov/htmlorg/lpb018/land/cfc00415.jpg
89	89-VBK-57	-	57	1987	-	R.B. Marshall	1898	
90	90-VBK-60	-	60	1987	0351a	C.D. Walcott	1897	http://libraryphoto.cr.usgs.gov/htmlorg/lpb390/land/wcd0351a.jpg
91	91-VBK-62	-	62	1988	-	R.B. Marshall	1909	
92	92-VBK-63	-	63	1988	-	R.B. Dole	1913	
93	93-VBK-65	-	65	1989	-	NPS	c1923	
94	94-VBK-66	-	66	1988	316	F.E. Matthes	1914	http://libraryphoto.cr.usgs.gov/htmlorg/lpb025/land/mfe00316.jpg
96	96-VBK-72A	-	72	1988	348	F.E. Matthes	1917	http://libraryphoto.cr.usgs.gov/htmlorg/lpb025/land/mfe00348.jpg
97	97-VBK-73	-	73	1988	-	NPS	1939	
98	98-VBK-74	-	74	1987	69	R.B. Marshall	1909	http://libraryphoto.cr.usgs.gov/htmlorg/lpb029/port/topa0069.jpg
99	99-VBK-75	-	75	1987	409	F.C. Calkins	1913	http://libraryphoto.cr.usgs.gov/htmlorg/lpb018/land/cfc00409.jpg
100	100-VBK-76	-	76	1988	3150	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/land/ggk03150.jpg
101	101-VBK-78	-	78	1988	3152	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/land/ggk03152.jpg
102	102-VBK-79	-	79	1988	3109	G.K. Gilbert	1907	http://libraryphoto.cr.usgs.gov/htmlorg/lpb176/land/ggk03109.jpg