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 20th and early 21st 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.