CHANGES AT TREELINE WITHIN THE SAN JUAN MOUNTAINS OF COLORADO

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by

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APPROVAL

The undersigned, appointed by the Associate Vice Chancellor of the Office of Research and Graduate Studies, have examined the thesis entitled

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a candidate for the degree of Master of Arts, and hereby certify that, in their opinion, it is worthy of acceptance.

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ABSTRACT

Repeat photography is a field method to study landscape change over time, yet most studies use a single pair of photographs spanning upwards of a century or more to ascertain change. In this study, I used repeat photography to study vegetation change across high-elevation environments within the San Juan Mountains of southwestern Colorado on decadal time scales. At five photo sites, I compared present conditions to both a historical photograph (ca. 1875–1910) and one from 2002 to determine if climate-induced thresholds have impacted high-elevation forests. Results from this research suggest that (1) tree establishment is increasing at 80% of photo sites and (2) spruce beetle-induced mortality is evident at 60% of sites. To increase the temporal resolution of when the spruce beetle outbreak occurred, I used remote sensing change detection analysis for the periods 2003–2011 and 2011–2019., Given the level of change detected between 2011–2019, spruce beetle-induced mortality along upper treeline likely originated within the past eight years. Overall, results from repeat photography used in conjunction with remote sensing provide multiple lines of evidence that ecological change had a resulted from the crossing of a climate threshold over the past decade. Findings from this research suggest that hotter drought is already impacting high-elevation treeline environments in parts of the San Juan Mountains.

Key Words: Repeat Photography, Engelmann Spruce, Remote Sensing, Quaking Aspen, San Juan Mountains, Colorado

1. INTRODUCTION

Climate patterns all across the world have followed a nonlinear path toward years dominated by above average temperatures as well as infrequent precipitation patterns starting during the 1950's and continuing until the present day (Huang et al. 2011; Anderegg et al. 2013; Rangwala and Miller,2010). Such changes in climate have the power to irrevocably alter particular ecosystems specifically ones already limited by both temperature and moisture regimes (Rocca et al.2014). Researchers argue that climate change has caused the world to enter the Anthropocene, a new geological epoch that has seen humanity ultimately alter all aspects of the earth from the carbon component within the atmosphere down to the geologic strata (Mauelshagen, 2014). Entering a new geologic epoch characterized by a different climate system begs the question of how will certain climatically-sensitive environments in the San Juan Mountains (SJM) of southwestern Colorado respond to such unpredictable and unprecedented climate variability?

Within western North America, instances of prolonged above average temperatures or hotter drought have become more frequent and less episodic since the year 2000 (Anderson et al.2009; Huang et al.2011; Anderegg et al. 2013; Rangwala and Miller,2010). Seager et al. (2007) discussed for instance how between 1998 and 2004 the western United States experienced hotter than average drought, attributed to a La Niña–like state of weather patterns dominating the eastern tropical Pacific followed up by weaker La Nina weather patterns from 2002 to 2004 (Rangwala and Miller, 2010). Overall however, the western portion of North America remained in a state of constant drought despite weakening La Nina conditions the following year. The SJM were no exception, where mean temperature increased by about 1 °C between 1990 – 2005 (Rangwalla and Miller, 2010). Such sharp increases in average temperatures on a decadal timescale provides evidence that the area of the SJM could have conceivably crossed an ecological threshold within that time frame.

As the climate of the SJM shifts towards weather patterns dominated by heat-induced drought stress, or hotter drought (after Allen et al. 2015), the concern then becomes how will such fluctuations impact high elevation subalpine forests across the region? Years of hotter drought have weakened the natural defense mechanisms of individual tree species and lead them to being more susceptible to attack by fungal pathogens and beetle attacks (Hart et al. 2015). The current infestation of spruce beetles (*Dendroctonus rufipennis*), for example has impacted over 325,000 ha of Engelmann spruce (*Picea engelmannii*) across the spruce-fir forest belt within the SJM and the southern Rocky Mountains as a whole since it began in the late 1990s (Andrus et al.2020).

In addition to disturbance regimes taking place with shorter time intervals in between, increased establishment at treeline has been witnessed not only within the SJM, but across a broad latitudinal gradient in the Rocky Mountains (Elliott and Baker, 2004; Elliott and Cowell, 2015; Elliott and Petruccelli, 2018). Quaking aspen (*Populus tremuloides*), a native deciduous tree of the Rocky Mountains was witnessed invading into conifer patches dominated by Engelmann spruce and subalpine fir (*Abies lasiocarpa*) and attributed to a decrease in mean spring precipitation and increased mean summer maximum temperature with the episodes of invasion all occurring after the year 1900. These instances continue to help provide evidence that an ecological threshold could have been passed within the Southern Rocky Mountains, but rates of change since the turn of the century are less clear.

To determine what environmental changes have occurred since 2002 across high-elevation subalpine forests, I conducted a repeat photography study at five locations within the SJM during the summer of 2019 (**Fig. 1**). I selected these sites because they exhibited minimal amounts of change during the 20th century when first compared in 2002 (Elliott 2003). I hypothesized that due to the continued intensification of hotter drought, as well as infestations due to spruce beetle becoming more widespread, that visual evidence of a climate-induced ecological threshold would be evident within the SJM over the past 17 years. Studying climatically sensitive environments at treeline through the use of repeat photography is crucial in order to determine how rapidly environmental changes are taking place on a decadal scale as we progress into the Anthropocene.

2. STUDY AREA

The San Juan Mountains are composed primarily of Tertiary volcanic rock with the oldest rocks lying within an area dominated by metamorphic schists and gneisses with most being sedimentary in origin (Larsen & Cross, 1956). The Tertiary volcanic rocks within the mountain range fall within four distinct groups, the Lake Fork quartz latite, San Juan tuff, and Silverton volcanic series in the western area; the pre-Potosi of the eastern area; the Potosi volcanic series and Fisher quartz latite; and the Hinsdale formation of which the resulting separation of tertiary rock being the result of deformation having taken place over a long period of erosion (Larsen & Cross, 1956). The volcanic activity of the region occurred primarily during the middle Miocene time and continued into the Quaternary. Within the western portion of the San Juan Mountains, the Mesozoic rocks that are present differ greatly from those found on the eastern side of the range due in part to the eastern portion being composed predominantly of latite, rhyolite, and dark olivine-quartz latite (Larsen & Clark, 1956).

The climate patterns of the San Juan Mountains vary in part due to the pervasive elevational differences that accompany the topographic complexity of the region. Precipitation in the SJM predominantly falls in the form of snow from typically mid-November until early May (Bovis

1977). During the summer months precipitation falls in the form of rainfall from July through the end of August, coinciding with the summer monsoon that dominates the region at this time (Marwitz, 1980). For comparison among study sites in the SJM, Uncompaghre peak at over 4,300 m receives an annual precipitation of over 1066.8mm with a mean annual temperature of -0.83°C (**Fig. 2 and 3**). This differs from the lower lying Mount Hesperus of the La Plata Mountain sub range at 1281.43 mm with a mean annual temperature of 1.17°C (**Fig. 4 and 5**) (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 28 April 2020.). The modest difference of 304 meters between the two individual peaks further brings to light how important a factor elevation is in what temperature and precipitation pattern dominates an individual location in comparison with another, indicating how even a slight, if not modest change in annual climate could potentially cause changes within the physical landscape (Wu et al. 2011).

Within higher elevations lie the spruce-fir forest that make up a majority of the vegetational component of the subalpine zone within the SJM. Located roughly between 2500 – 3000 m, the spruce-fir forest is composed predominantly of Engelmann spruce and Subalpine fir while also being intermixed with quaking aspen (Aplet et al. 1988). Within the SJM, certain areas at treeline have had a history of cattle grazing and I witnessed evidence of ongoing grazing at one of my sites in the La Platas (Hansen and Reid, 1975).

3. METHODS

3.1 Repeat Photography

Photo Selection and Comparison

The photographs utilized initially came from Elliott (2003) in which they were originally gathered from the Colorado Historical Society, the U.S. Geological Survey Photographic Library, and the Western History Collection at the Denver Public Library. The photographs used for comparison were all captured during the same period of time in which they were taken during the summer of 2002 (**Table 1**). The same location and angles were also employed as well as encapsulating the images during the same time of day in which they had previously been taken.

This repeat photography study differed from prior studies due to the unique aspect of it comparing the rate of environmental change over time spans of a century as well as on a decadal time scale with three photo points rather than two which is often used within conventional repeat photography experiments. The three photo points under comparison are one historical late nineteenth/early twentieth century photograph, one taken during the summer of 2002 and one taken during the summer of 2019. The benefits of the small-scale nature of this study was the greater allotment of time and effort given to analyzing each site compared.

Field Work

I located and rephotographed the historical photos using topographic maps and field notes that accompanied the original photos. When the exact photograph location was not immediately clear, I analyzed the surrounding landscape to identify and align physical features such as nearby mountain peaks, prominent rock outcroppings, and/or large boulders identifiable in the foreground. This is a trial-and-error process of repeated moves with a camera until the scene best matches the original (Elliott & Baker, 2004). The repeat photos taken were captured through the use of a digital camera atop a tripod to aid in capturing the image of the site.

Data Analysis

Examination of each photo site was done once the scene was captured. Initial analysis included taking note of whether new vegetation had appeared, if a disturbance event occurred namely in the form of wildfire or insect infestation, or if perhaps human modification of the landscape had happened within the time interval of 2002 to 2019. Environmental change witnessed taking place between that time span were then compared back to the historical photographs in order to determine if the modifications witnessed were part of a broader trend taking place. All information was recorded on field sheets that were brought into the field. In addition to documenting environmental change of each site, the time of day, weather conditions, and GPS coordinates were also written down as well.

3.2 Remote Sensing

Gathering of the remote sensing imagery came from the United States Geological Survey (USGS) Earth Explorer website. A list of specifications was designated to allow for the most suitable data to be utilized. Dates were first narrowed down for the Landsat 5 series between January 1st, 2003 up until December 31st, 2011 due to the Landsat 5 series becoming discontinued on June 24th, 2013 (Egorov et al.2019). Dates were then narrowed down further within the initial search criteria to only allow imagery from June through August to appear, representing the peak of the growing season within the SJM. Selection of the image sensor was then followed up by specifying the correct row and path combination for the specific location over the SJM. The row and path groupings are based on the worldwide reference system, a global system that catalogs Landsat data by matching the row and paths that each of the satellites themselves follow around the globe (Wulder & Seeman, 2001). The area corresponding to where the photo site is located within SJM lies within path 34, row 35. Cloud coverage specification was then designated for the imagery employed. Cloud coverage was put at 10% in order to compensate for the summer monsoon season that takes place within the San Juan Mountains between the months of July and August. Once downloaded the Environment for Visualizing Images (ENVI) remote sensing software layer stacking tool was utilized in order to stack each singular band for each date into one piece of imagery.

Rather than utilizing the entire Landsat scene, clipping out the desired area of the image was done to emphasize the area of the SJM where change had taken place. Through the use of ArcMap, clipping the specific area in this case the Uncompahgre Peak and Wetterhorn Peak photo sites was done through first creating a personal geodatabase within the folder connection of the ArcCatalog. Afterwards, the area under interest would be defined by creating a free hand polygon (**Fig.6 – 11**). The free hand method was utilized in order to avoid extracting parts of the imagery that contained snow cover of which the 2011 imagery largely exhibited.

Within ENVI, a change detection analysis was then conducted in order to offer further evidence that changes had occurred by analyzing imagery at two of the photo sites that witnessed dramatic change for between 2003 – 2011 and 2011 - 2019. Within ENVI, the image change workflow was enabled and the 2003 and 2011 scenes were both put into each individual time files. Next automatically registering the images together was done by registering the matching bands as band 2 green band due to it emphasizing peak vegetation (Campbell and Wynne, 2011). Image difference was then selected followed by enabling the spectral angel difference. Afterwards, the change of interest was selected in order to show only a decrease in pixel value from the change detecting in order to highlight the change taking place between the two scenes. The auto thresholding option was selected as Otsu's due to the method being able to select the threshold between the two scenes by minimizing the within-class variance of the two groups of pixels separated by the thresholding operator (Campbell and Wynne, 2011). The same process was repeated for the 2011 – 2019 change detection.

4. RESULTS

Boren's Gulch

Boren's Gulch located within the La Plata Mountain sub range was the only site that experienced an increase in establishment of quaking aspen. Quaking aspen had first appeared within the 2002 photo site in comparison to the historical photograph taken in 1875 (**Fig. 12**). Between 2002 and 2019, the quaking aspen component appears to have continued that trend first noticed. The aspen stands appeared in dense thickets with much new vegetation appearing underneath older, existing stands. The vegetation also appeared to be in good health judging from the vibrant appearance of the foliage without any signs of mortality or drought stress. The location of the aspen stands also appears to have been expanding in range as well due to how the grove within the scène appeared to have migrated further upslope more than what is evident in the 2002 photo.

Mount Hesperus

Mount Hesperus is also located within the La Plata mountains and experienced environmental change with increased establishment in the form of the standing krumholtz patch that first appeared between 1905 and 2002 continuing to expand outward (**Fig. 13**). In comparison to the 2002 and 2019 images, the krumholtz patch appears to have expanded out further right and also appears to have become thicker, indicating trees growing more denser while still expanding outward.

Uncompahgre Peak

Within the scene for Uncompaghre Peak, an increase in seedling establishment had taken place between 2002 to 2019. Within the center hand portion of the scene, there is an increase in the presence of young saplings compared with the last photograph in 2002 (**Fig. 14**). This increase in establishment continues the trend witnessed between the late 1800s and 2002 when establishment was first witnessed taking place. Within the photo site as well, spruce beetle mortality can be seen within the lower right-hand portion of the image coinciding within an area dominated by the spruce-fir forest (**Fig. 14**). However, within the initial pair of repeat photos for Uncompahgre Peak, the extent of damage attributed to by spruce beetle appears to be rather limited and not as widespread considering that only a small portion of spruce-fir forest is visible within the scene itself. Photographs taken along the periphery of Uncompahgre Peak, however highlight the true scope of damage inflicted upon the Engelmann spruce component of the spruce fir-forest within the area (**Fig.15-17**). Large portions of the scene exhibit mortality, as evidenced by the majority of forest showing standing dead grey trees. The change detection analysis conducted further highlights change having taken place within the spruce-fir forested areas within the periphery of Uncompahgre Peak. Between 2003 and 2011, pixel change occurred in pockets rather than in large continuous blocks of pixel change as compared with the 2011 and 2019 change detection that witnessed an increase in small clusters of change, predominantly within areas of spruce-fir forest (**Fig.18 and 19**). It can therefore be inferred that spruce beetle-induced mortality began in this immediate vicinity after 2011.

Wetterhorn Peak

In the Wetterhorn Peak photo site, change occurred in the form of spruce beetle damage upon the Engelmann spruce portion of the spruce-fir forest throughout the image. The mortality can be visualized near the center left hand portion of the scene with continuous blocks of forest appearing as standing dead forest, exhibiting the typical appearance of grey discoloration associated with that of a recent outbreak by spruce beetles (**Fig. 20**). When looking in contrast to the area of beetle kill located higher up within the scene to areas located lower in elevation, the presence of beetle kill looks to dissipate as the elevation decreases. The change detection analysis conducted provided further evidence of change taking place within the spruce-fir forest of the area. Within the 2003 – 2011 detection, change occurred primarily within the portion of the scene corresponding with areas of spruce-fir forest as large blocks of connected pixels with a majority of the scene not experiencing change (**Fig. 21**). This contrasts sharply with the 2011 – 2019 change detection that saw almost all of the scene displaying changes in pixel value with only isolated pockets not having experienced alterations (**Fig. 22**).

Broken Hill

Within the Broken Hill photo site, increased establishment was observed within the center hand portion of the scene from the individual Engelmann spruce tree increasing in size and diameter as compared to when last photographed in 2002 (**Fig. 23**). Within the upper center portion of the photo, new establishment was also witnessed within close proximity of standing mature Engelmann spruce trees that were there prior.

The Broken Hill photo site showed the least amount of damage from spruce beetle when compared to either Wetterhorn or Uncompahgre Peak in the same general vicinity of the SJM (**Fig. 1**). Rather than appearing in large clusters of beetle kill as was the case with the previous two sites, the level of die back within the area appears in the form of scattered, individual trees surrounded by otherwise healthy spruce-fir forest (**Fig. 23**). This perhaps indicates that the infestation at Broken Hill began only recently because it would likely have larger portions of standing dead grey trees if beetles had been actively invading this scene for many years prior.

<u>5. DISCUSSION</u>

5.1. ***Patterns of tree establishment***

Quaking Aspen

Quaking aspen was found becoming more established at treeline within Boren's Gulch (**Fig. 12**) continuing the trend first witnessed from Elliott and Baker (2004) as well as one other study having seen an increase in its presence throughout western North America (Cole et al. 2009). Circumstances around Boren's Gulch within the La Plata Mountains points to environmental conditions having continued to favor establishment of quaking aspen over Engelmann spruce or sub alpine fir. Other studies within the San Juan Mountains as well have seen aspen invading into areas typically dominated by shrubs and grasses (Zier and Baker, 2006). Kulakowski et al. (2004) had also witnessed quaking aspen becoming more prominent over a 175 000-ha study area within western Colorado when comparing quaking aspen components from the late 19th century up until the end of the 20th century. These results provide evidence suggesting that aspen invaded areas of conifer forest even in the absence of fire that normally initiates them to propagate and reproduce. Many have argued that as disturbance regimes become more prominent with shorter return intervals that quaking aspen will start to become the dominant tree species within subalpine forests due to their ability to thrive and proliferate following a disturbance event (Manier and Laven, 2002; Kulakowski et al. 2012; Rogers et al. 2013).

However, Huang et al. (2011) noted a massive decline in quaking aspen within the San Juan National Forest from June–August of 2009–2011, because of severe drought in concert with above average temperatures, the hallmark of hotter drought (Allen et al. 2015); causing sudden aspen decline (SAD). Anderegg et al. (2012) also connected quaking aspen decline throughout the western United States with years of continued drought causing hydraulic deterioration leading to cavitation within quaking aspen. This discord highlights how quaking aspen as a whole does not follow a linear path in responding either positively or negatively to climate dominated by prolonged heat-induced drought stress.

Engelmann Spruce and Subalpine Fir

Engelmann spruce and sub alpine fir also witnessed patterns of establishment similar to what was observed amongst the quaking aspen from this field research (**Figs. 13,14, and 23**). Within areas at treeline, growth of saplings as well as new establishment is often hampered due in part by the harsh winds and colder temperatures that dominate the environment (Resler et al. 2005; Malanson et al. 2007). Within scenes from Broken Hill, Uncompahgre Peak, and Mount Hesperus I hypothesized that the increase in establishment took place due to the rising annual minimum and mean temperatures that have been measured across the San Juan Mountains (**Figs. 2-5**) as well as due to protection from neighboring mature trees against wind desiccation. Elliott. (2012) found that temperature variables exceeding bioclimatic thresholds were the main driver in abrupt establishment at treeline taking place within the Rocky Mountains during the latter half of the 20th century. This main point is similar to how both Uncompahgre Peak and Mount Hesperus witnessed an increase in both minimum and mean temperatures and also experienced an increase in establishment, further supporting the notion that climate within the SJM has shifted towards conditions that promote continued tree establishment.

This study provides evidence that protection from nearby trees facilitated further tree establishment at upper treeline. Wind within alpine environments has the ability to restrict tree height and growth, resulting in asymmetric and suppressed growth, such as krummholz, that are common within a treeline ecotone (Holtmeier and Broll, 2013). On Broken Hill, establishment was seen along the periphery of already existing mature tall Engelmann spruce (**Fig. 13**). Uncompahgre peak's area of establishment was also found within preexisting stands of saplings albeit not as tall as the stands already existing at Broken Hill (**Fig. 23**). These examples of existing “shelter sites” in addition accompanied by an increase in temperature trends could conceivably have contributed to the increase in establishment of both Engelmann spruce and subalpine fir (McIntire et al. 2016).

5.2. *Spruce beetle induced mortality*

Repeat photography exposed the fact that climate-induced thresholds since 2002 have triggered spruce beetle-induced mortality along the uppermost extent of subalpine forest at treeline. Numerous studies have attributed ongoing spruce beetle infestations to the pervasive drought-like conditions that have plagued southwestern Colorado in general and the SJM more specifically, since 2000 (Pielke et al.2002; Anderegg et al. 2011; Hart et al.2014; Berner et al. 2017; Carlson et al. 2017;). Although droughts are cyclical in nature, the rate in which they have been occurring has increased as well as their intensity (Carlson et al. 2017). Prolonged drought-like conditions weaken the defense mechanisms of numerous conifer species such as Engelmann spruce, making them more susceptible to a disturbance an attack from spruce beetles (Veblen et al. 1994; Jaimeson et al.2012). In addition to weakening the protective measures of particular species, drought and warmer temperatures enable spruce beetle populations to live longer than one growing season and be able to survive throughout the winter months due to the lack of frigid temperatures that would normally keep their populations in check (Veblen et al. 1991; Hart et al.2014; Temperli et al. 2015). The combination of these potent abiotic factors has contributed to the current spruce beetle infestations taking place within the southern Rocky Mountains with over 325,000 ha of spruce-fir forest having been impacted from 2005 to 2017 alone (Andrus et al.2020).

Perhaps most compelling, the photo sites within this study that witnessed tree mortality by spruce beetle (**Figs.13-23**) offer the first instances of spruce beetle morality at treeline within the SJM and the Southern Rocky Mountains more broadly. Under normal climactic regimes these areas would not experience such devastation by bark beetles as an active disturbance agent due to the otherwise frigid temperatures that dominate treeline (Holtmeier and Broll, 2018). However, reoccurring instances of hotter drought accompanied by a decrease in annual precipitation between 2002 and 2019 have led to the instances of spruce beetle becoming an active disturbance agent within areas at treeline (Sauliener et al. 2020). This also leads to the possibility that as hotter drought becomes more reoccurring at treeline that spruce beetle will begin to become more of an active disturbance agent (Petttit et al. 2019). Consecutive episodes of spruce beetle outbreaks within the spruce-fir forests also begs the question going forward of how will regeneration of this sensitive ecosystem be characterized? Hart et al. (2014) saw multispecies stands within the eastern San Juan Mountains see a shift in species composition from the main preexisting canopy species to nonhost species, suggesting low potential for compositional recovery for overstory species prior to infestation. This suggests the possibility of the subalpine forests shifting over from being composed primarily of Engelmann spruce to perhaps more subalpine fir in addition to other species that can take advantage of drier environments brought on by hotter drought (Allen and Breshears,1998)

6. CONCLUSION

Overall, the outcomes of this study support the idea that hotter drought has and is currently impacting treeline, which has triggered an ecological threshold response over the past 17 years (2002 – 2019). The ecological threshold passed within the San Juan Mountains explains the witnessed increase in tree establishment at treeline as well as the forest mortality from spruce beetle that has not been previously reported. As hotter drought continues to become more reoccurring across the Southern Rocky Mountains, high-elevation mesic environments, such as those in the San Juan Mountains, will need to be studied and monitored more in order to see what changes unfold. Ultimately, the fate of spruce-fir forests will depend largely on how frequently hotter drought will continue to occur, where instances of an increase in establishment can transpire as well occurrences of spruce beetle on the forests of the subalpine zone.

7. REFERENCES

Allen, C. D., and D. D. Breshears. "Drought-induced Shift of a Forest-woodland Ecotone: Rapid Landscape Response to Climate Variation." Proceedings of the National Academy of Sciences 95, no. 25 (1998): 14839-4842.

Anderegg, Leander D. L., William R. L. Anderegg, John Abatzoglou, Alexandra M. Hausladen, and Joseph A. Berry. "Drought Characteristics Role in Widespread Aspen Forest Mortality across Colorado, USA." Global Change Biology 19, no. 5 (2013): 1526-537.

Anderegg, W. R. L., J. A. Berry, D. D. Smith, J. S. Sperry, L. D. L. Anderegg, and C. B. Field. "The Roles of Hydraulic and Carbon Stress in a Widespread Climate-induced Forest Die-off." Proceedings of the National Academy of Sciences 109, no. 1 (2011): 233-37.

Anderegg, William R. L., Lenka Plavcová, Leander D. L. Anderegg, Uwe G. Hacke, Joseph A. Berry, and Christopher B. Field. "Droughts Legacy: Multiyear Hydraulic Deterioration Underlies Widespread Aspen Forest Die-off and Portends Increased Future Risk." Global Change Biology 19, no. 4 (2013): 1188-196.

Andersen, Tom, Jacob Carstensen, Emilio Hernández-García, and Carlos M. Duarte. "Ecological Thresholds and Regime Shifts: Approaches to Identification." Trends in Ecology & Evolution 24, no. 1 (2009): 49-57.

Andrus, Robert A., Sarah J. Hart, and Thomas T. Veblen. "Forest Recovery Following Synchronous Outbreaks of Spruce and Western Balsam Bark Beetle Is Slowed by Ungulate Browsing." Ecology, 2020.

Aplet, Gregory H., Richard D. Laven, and Frederick W. Smith. "Patterns of Community Dynamics in Colorado Engelmann Spruce-Subalpine Fir Forests." Ecology 69, no. 2 (1988): 312–19.

Berner, Logan T, Beverly E Law, Arjan J H Meddens, and Jeffrey A Hicke. "Tree Mortality from Fires, Bark Beetles, and Timber Harvest during a Hot and Dry Decade in the Western United States (2003–2012)." *Environmental Research Letters* 12, no. 6 (January 2017): 065005.

Bovis, Michael J. “Statistical Forecasting Of Snow Avalanches, San Juan Mountains, Southern Colorado, U.S.A.” Journal of Glaciology 18, no. 78 (1977): 87–99.

Campbell, James B., and Randolph H. Wynne. Introduction to Remote Sensing. New York: Guilford Press, 2011.

Carlson, Amanda R., Jason S. Sibold, Timothy J. Assal, and Jose F. Negrón. “Evidence of Compounded Disturbance Effects on Vegetation Recovery Following High-Severity Wildfire and Spruce Beetle Outbreak.” Plos One 12, no. 8 (April 2017).

Cole, Christopher T., Jon E. Anderson, Richard L. Lindroth, and Donald M. Waller. “Rising Concentrations of Atmospheric CO2 Have Increased Growth in Natural Stands of Quaking Aspen (Populus Tremuloides).” Global Change Biology 16, no. 8 (2009): 2186–97.

Egorov, Alexey, David Roy, Hankui Zhang, Zhongbin Li, Lin Yan, and Haiyan Huang. “Landsat 4, 5 and 7 (1982 to 2017) Analysis Ready Data (ARD) Observation Coverage over the Conterminous United States and Implications for Terrestrial Monitoring.” Remote Sensing 11, no. 4 (2019): 447.

Elliott, G.P. (2003) Quaking aspen (Populus tremuloides Michx.) and Conifers at Treeline: A Century of Change in the San Juan Mountains, Colorado, USA. Master's Thesis, University of Wyoming, Laramie, WY

Elliott, Grant P. "Extrinsic Regime Shifts Drive Abrupt Changes in Regeneration Dynamics at Upper Treeline in the Rocky Mountains, USA." Ecology 93, no. 7 (2012): 1614-625.

Elliott, Grant P., and C. Mark Cowell. "Slope Aspect Mediates Fine-Scale Tree Establishment Patterns at Upper Treeline during Wet and Dry Periods of the 20th Century." Arctic, Antarctic, and Alpine Research 47, no. 4 (2015): 681-92.

Elliott, Grant P., and Christopher A. Petruccelli. "Tree Recruitment at the Treeline across the Continental Divide in the Northern Rocky Mountains, USA: The Role of Spring Snow and Autumn Climate." Plant Ecology & Diversity 11, no. 3 (2018): 319-33. (Elliott & Petruccelli, 2018)

Elliott, Grant P., and William L. Baker. "Quaking Aspen (Populus Tremuloides Michx.) at Treeline: A Century of Change in the San Juan Mountains, Colorado, USA." Journal of Biogeography 31, no. 5 (2004): 733-45.

Frankl, Amaury, Jan Nyssen, Morgan De Dapper, Mitiku Haile, Paolo Billi, R. Neil Munro, Jozef Deckers, and Jean Poesen. "Linking Long-Term Gully and River Channel Dynamics to Environmental Change Using Repeat Photography (Northern Ethiopia)." Geomorphology 129, no. 3-4 (2011): 238–51.

Hansen, R. M., and L. D. Reid. "Diet Overlap of Deer, Elk, and Cattle in Southern Colorado." Journal of Range Management 28, no. 1 (1975): 43.

Hart, Sarah J., Thomas T. Veblen, Karen S. Eisenhart, Daniel Jarvis, and Dominik Kulakowski. "Drought Induces Spruce Beetle (Dendroctonus Rufipennis) Outbreaks across Northwestern Colorado." Ecology 95, no. 4 (2014): 930–39.

Hart, Sarah J., Thomas T. Veblen, Nathan Mietkiewicz, and Dominik Kulakowski. "Negative Feedbacks on Bark Beetle Outbreaks: Widespread and Severe Spruce Beetle Infestation Restricts Subsequent Infestation." Plos One 10, no. 5 (2015).

Holtmeier, Friedrich-Karl, and Gabriele Broll. "Wind as an Ecological Agent at Treelines in North America, the Alps, and the European Subarctic." Physical Geography 31, no. 3 (2010): 203–33.

Holtmeier, Friedrich-Karl, and Gabriele Broll. "Subalpine Forest and Treeline Ecotone under the Influence of Disturbances: A Review." Journal of Environmental Protection 09, no. 07 (2018): 815–45.

Huang, Cho-Ying, and William R. L. Anderegg. "Large Drought-induced Aboveground Live Biomass Losses in Southern Rocky Mountain Aspen Forests." Global Change Biology 18, no. 3 (2011): 1016-027.

Jamieson, Mary A., Amy M. Trowbridge, Kenneth F. Raffa, and Richard L. Lindroth. “Consequences of Climate Warming and Altered Precipitation Patterns for Plant-Insect and Multitrophic Interactions.” Plant Physiology 160, no. 4 (May 2012): 1719–27.

Kulakowski, Dominik, Thomas T. Veblen, and Sarah Drinkwater. “The Persistence Of Quaking Aspen (Populus Tremuloides) In The Grand Mesa Area, Colorado.” Ecological Applications 14, no. 5 (2004): 1603–14.

Kulakowski, Dominik, Carolyn Matthews, Daniel Jarvis, and Thomas T. Veblen. “Compounded Disturbances in Sub-Alpine Forests in Western Colorado Favour Future Dominance by Quaking Aspen (Populus Tremuloides).” Journal of Vegetation Science 24, no. 1 (February 2012): 168–76.

Larsen, E.S. Jr. & Cross, W. (1956) Geology and petrology of the San Juan region southwestern Colorado. Geological Survey Professional Paper 258. US Department of the Interior, Washington, DC.

Landhäusser, Simon M., Dominique Deshaies, and Victor J. Lieffers. "Disturbance Facilitates Rapid Range Expansion of Aspen into Higher Elevations of the Rocky Mountains under a Warming Climate." Journal of Biogeography 37, no. 1 (2009): 68-76.

Malanson, George P., David R. Butler, Daniel B. Fagre, Stephen J. Walsh, Diana F. Tomback, Lori D. Daniels, Lynn M. Resler, et al. “Alpine Treeline of Western North America: Linking Organism-To-Landscape Dynamics.” Physical Geography 28, no. 5 (2007): 378–96.

Marwitz, John D. "Winter Storms over the San Juan Mountains. Part I: Dynamical Processes." Journal of Applied Meteorology 19, no. 8 (1980): 913-26.

Mauelshagen, Franz. “Redefining Historical Climatology in the Anthropocene.” The Anthropocene Review 1, no. 2 (2014): 171–204.

Pielke, Roger A., Nolan Doesken, Odilia Bliss, Tara Green, Clara Chaffin, Jose D. Salas, Connie A. Woodhouse, Jeffrey J. Lukas, and Klaus Wolter. “Drought 2002 in Colorado: An

Unprecedented Drought or a Routine Drought?” Weather and Climate: The M.P. Singh Volume, Part I, 2005, 1455–79.

Pettit, Jessika M., Julia I. Burton, R. Justin Derose, James N. Long, and Steve L. Voelker. “Epidemic Spruce Beetle Outbreak Changes Drivers of Engelmann Spruce Regeneration.” Ecosphere 10, no. 11 (2019).

PRISM Climate Group, Oregon State U. Accessed April 28th, 2020. http://www.prism.oregonstate.edu/explorer/.

Rangwala, Imtiaz, and James R. Miller. "Twentieth Century Temperature Trends in Colorado’s San Juan Mountains." Arctic, Antarctic, and Alpine Research 42, no. 1 (2010): 89-97.

Resler, Lynn M., David R. Butler, and George P. Malanson. “Topographic Shelter and Conifer Establishment and Mortality in an Alpine Environment, Glacier National Park, Montana.” Physical Geography 26, no. 2 (2005): 112–25.

Rocca, Monique E., Peter M. Brown, Lee H. Macdonald, and Christian M. Carrico. “Climate Change Impacts on Fire Regimes and Key Ecosystem Services in Rocky Mountain Forests.” Forest Ecology and Management 327 (2014): 290–305.

Rogers, Paul C., Cristina Eisenberg, and Samuel B. St. Clair. "Resilience in Quaking Aspen: Recent Advances and Future Needs." Forest Ecology and Management 299 (2013): 1-5.

Saulnier, M., J. Schurman, O. Vostarek, M. Rydval, J. Pettit, V. Trotsiuk, P. Janda, R. Bače, J. Björklund, and M. Svoboda. “Climatic Drivers of Picea Growth Differ during Recruitment and Interact with Disturbance Severity to Influence Rates of Canopy Replacement.” Agricultural and Forest Meteorology 287 (2020): 107981.

Seager, Richard. "The Turn of the Century North American Drought: Global Context, Dynamics, and Past Analogs*." Journal of Climate 20, no. 22 (2007): 5527-552.

Temperli, Christian, Thomas T. Veblen, Sarah J. Hart, Dominik Kulakowski, and Alan J. Tepley. “Interactions among Spruce Beetle Disturbance, Climate Change and Forest Dynamics Captured by a Forest Landscape Model.” Ecosphere 6, no. 11 (2015).

Veblen, Thomas T., Keith S. Hadley, Marion S. Reid, and Alan J. Rebertus. “The Response of Subalpine Forests to Spruce Beetle Outbreak in Colorado.” Ecology 72, no. 1 (1991): 213–31.

Veblen, Thomas T., Keith S. Hadley, Elizabeth M. Nel, Thomas Kitzberger, Marion Reid, and Ricardo Villalba. “Disturbance Regime and Disturbance Interactions in a Rocky Mountain Subalpine Forest.” The Journal of Ecology 82, no. 1 (1994):

Wu, Zhuoting, Paul Dijkstra, George W. Koch, Josep Peñuelas, and Bruce A. Hungate. "Responses of Terrestrial Ecosystems to Temperature and Precipitation Change: A Meta-analysis of Experimental Manipulation." Global Change Biology 17, no. 2 (2011)

Wulder, M., and D. Seemann. “Spatially Partitioning Canada with the Landsat Worldwide Referencing System.” Canadian Journal of Remote Sensing 27, no. 3 (2001): 225–31.

Zier, James L., and William L. Baker. "A Century of Vegetation Change in the San Juan Mountains, Colorado: An Analysis Using Repeat Photography." Forest Ecology and Management 228, no. 1-3 (2006): 251-62.

8. FIGURES AND TABLES

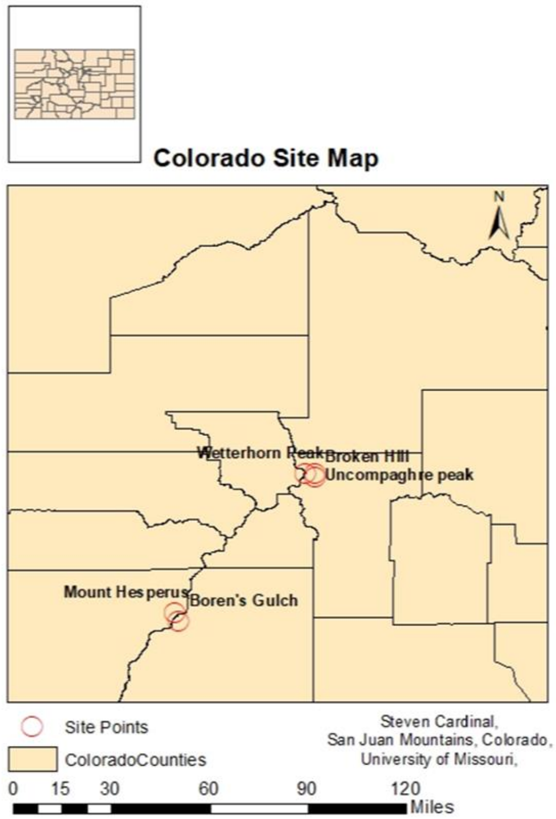

Fig 1. Study area within the San Juan Mountains, Colorado. Red, unfilled circles correspond to repeat photography sites.

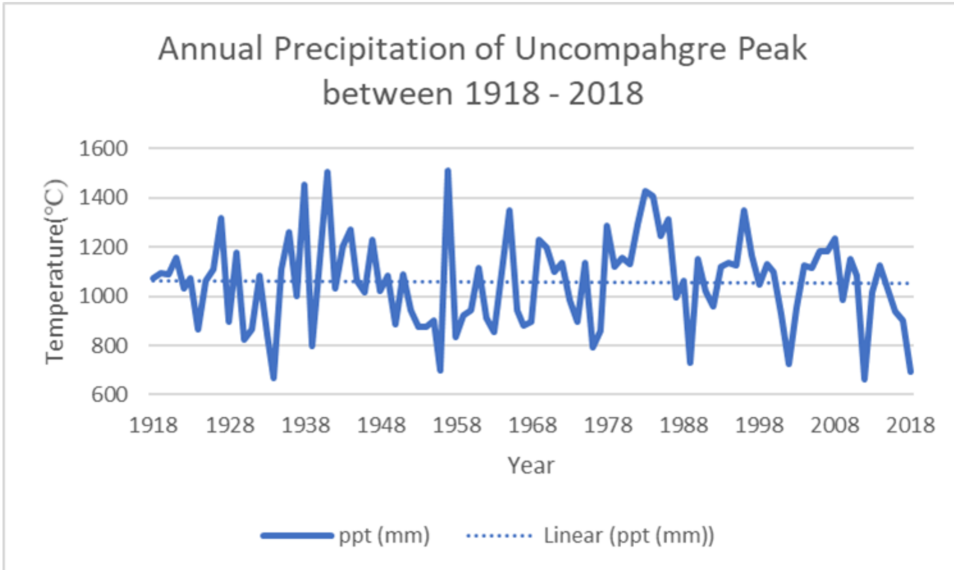

Fig 2. Annual precipitation of Uncompaghre Peak from 1918 – 2018. Source: PRISM Climate Group, Oregon State University.

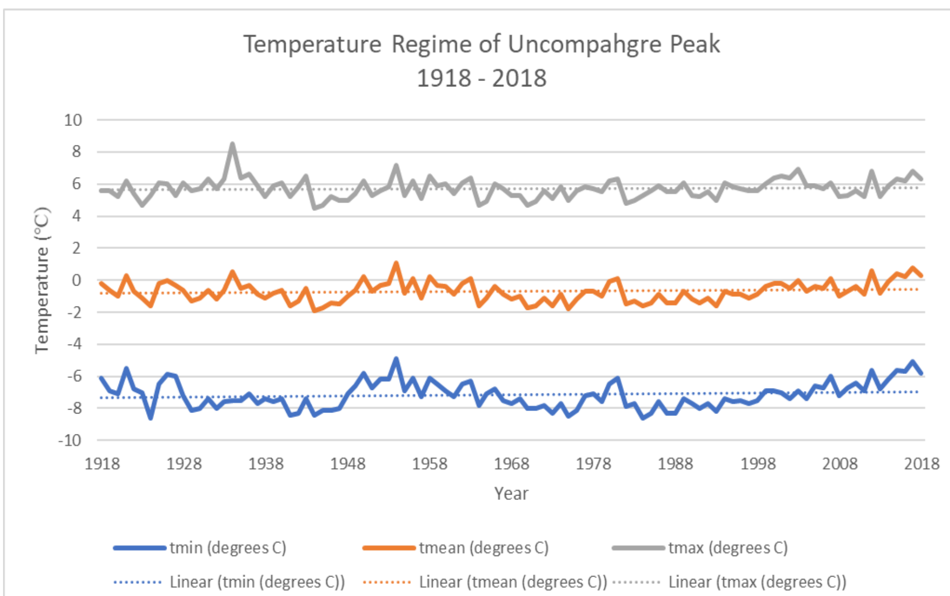

Fig 3. Temperature regime of Uncompaghre Peak from 1918 – 2018. Source: PRISM Climate Group, Oregon State University

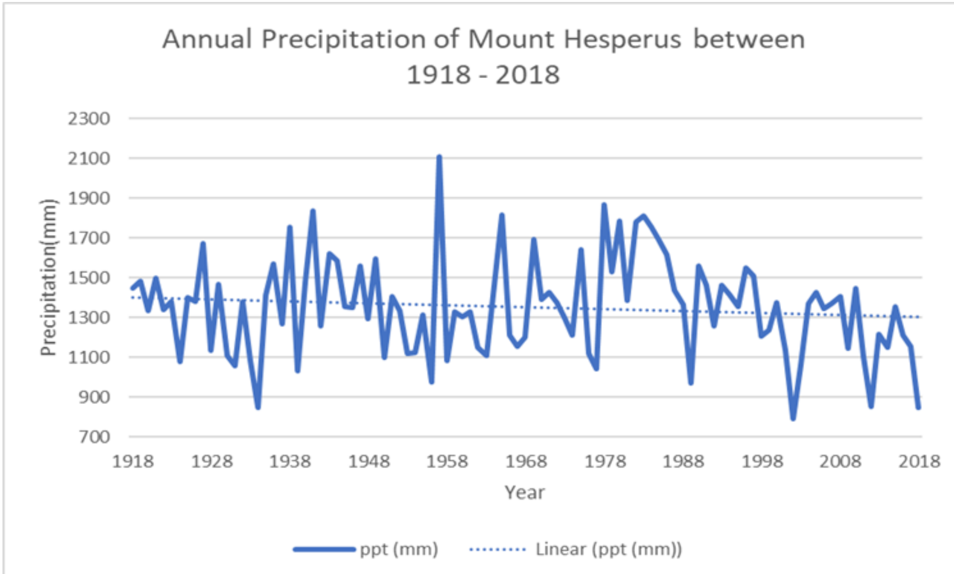

Fig 4. Annual precipitation of Mount Hesperus from 1918 – 2018. Source: PRISM Climate Group, Oregon State University.

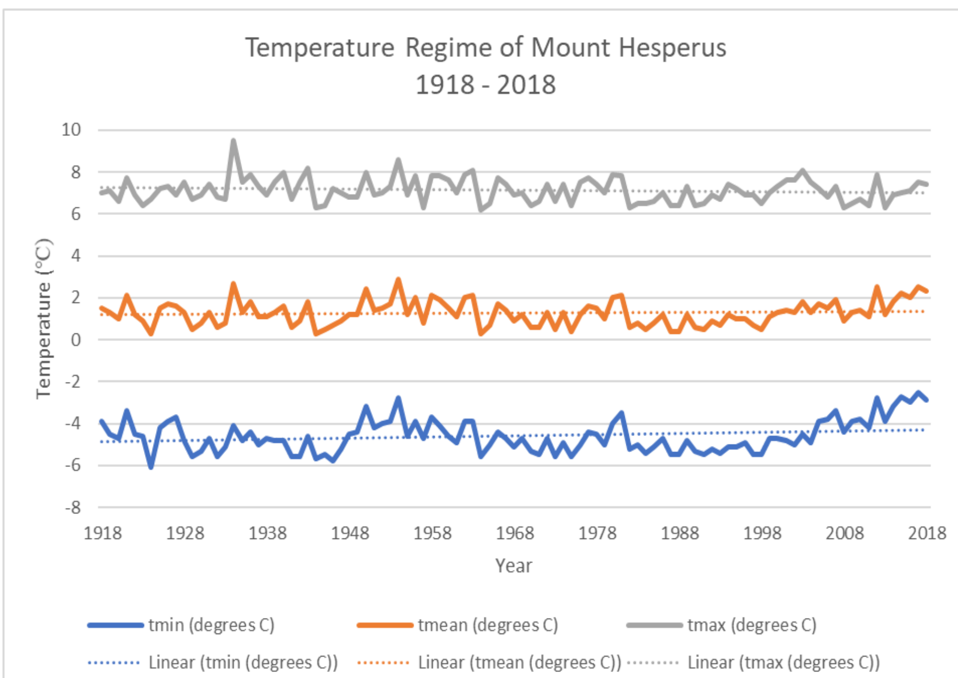

Fig 5. Temperature regime of Mount Hesperus between 1918 – 2018. Source: PRISM Climate Group, Oregon State University

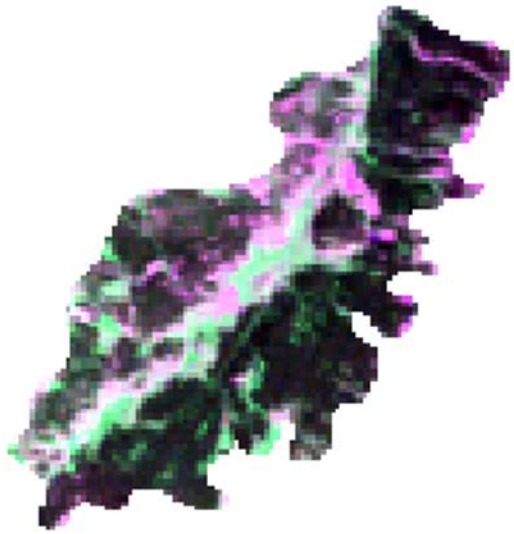

Fig 6. July 11th, 2003 Landsat 5 Multispectral image of Uncompaghre Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Data source: United States Geological Survey (USGS) EarthExplorer (EE) user interface, 2020

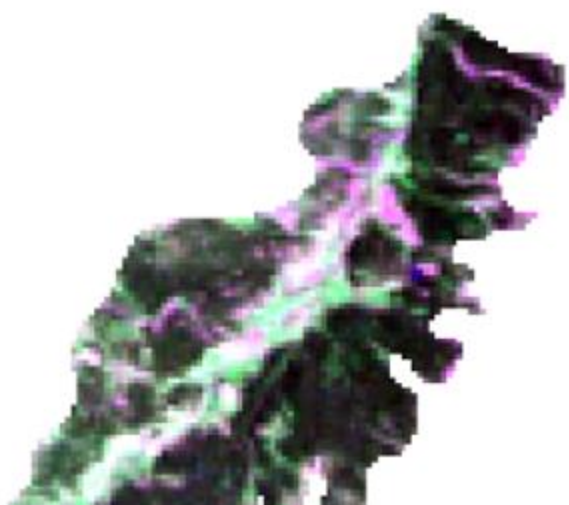

Fig 7. July 1st, 2011 Landsat 5 Multispectral image of Uncompaghre Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Data source: United States Geological Survey (USGS) EarthExplorer (EE) user interface, 2020

Fig 8. Landsat 8 August 24th, 2019 Multispectral image of Uncompaghre Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Data source: United States Geological Survey (USGS) EarthExplorer (EE) user interface, 2020

Fig 9. July 11th, 2003 Landsat 5 Multispectral image of Wetterhorn Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Data source: United States Geological Survey (USGS) EarthExplorer (EE) user interface, 2020

Fig 10. July 1st, 2011 Landsat 5 Multispectral image of Wetterhorn Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Data source: United States Geological Survey (USGS) EarthExplorer (EE) user interface, 2020

Fig 11. Landsat 8 August 24th, 2019 Multispectral image of Wetterhorn Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Data source: United States Geological Survey (USGS) EarthExplorer (EE) user interface, 2020

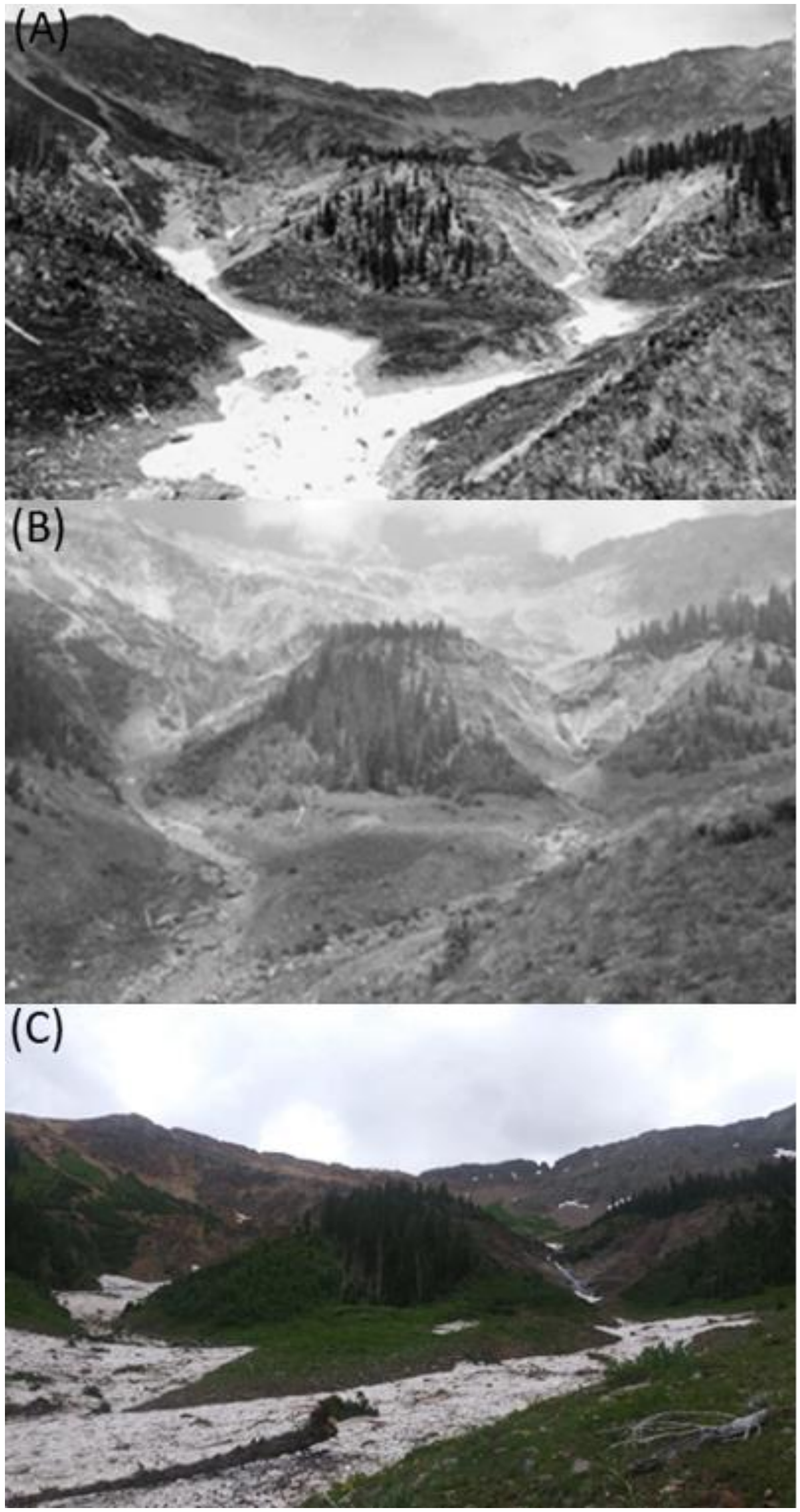

Fig 12. Photo site 1. View is to the northwest looking up into Boren's Gulch in the La Plata Mountains. The original photo (A) was taken by W.H. Jackson in 1875, (B) was taken by Grant P. Elliott in 2002 and (C) was taken during 2019. Source: United States Geological Survey Photographic Library, Denver, CO.

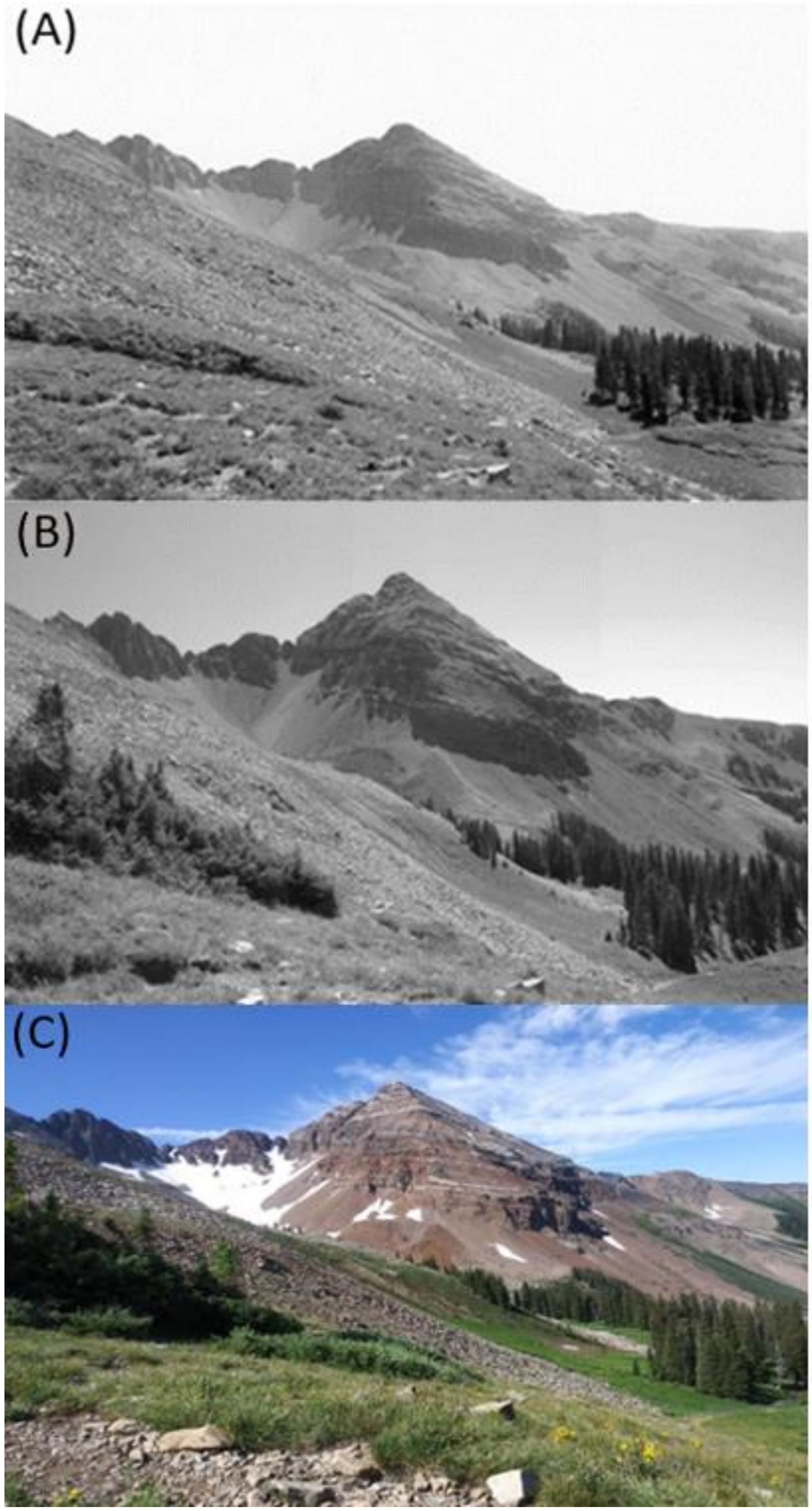

Fig 13. Photo site 3. View is to the southeast looking up into Mount Hesperus. The original photo (A) was taken by Cross, W. in 1896, (B) was taken by Grant P. Elliott in 2002 and (C) was taken during 2019.
Source: United States Geological Survey Photographic Library, Denver, CO.

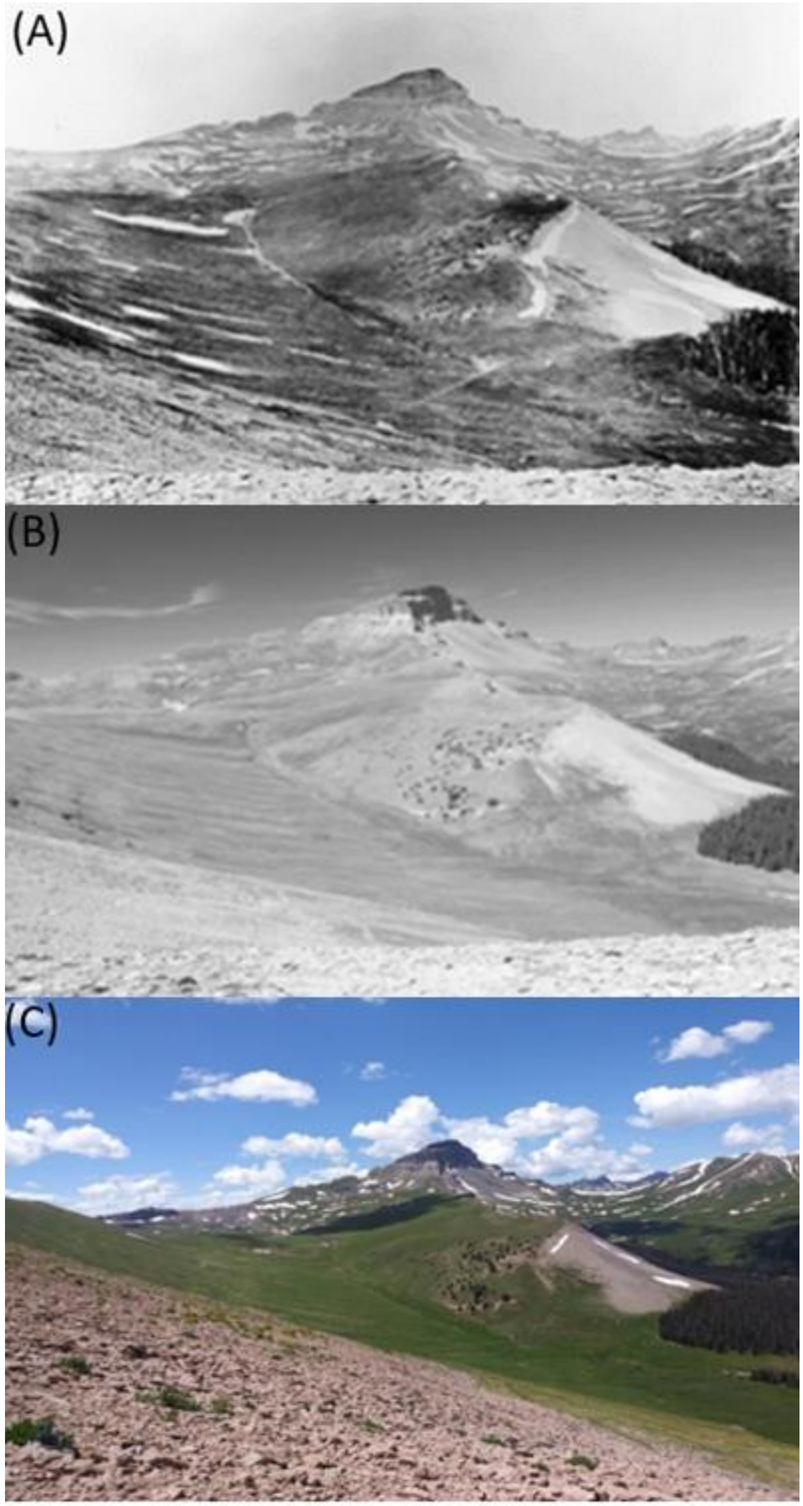

Fig 14. Photo site 2. View is to the southwest looking up into Uncompahgre Peak. The original photo (A) was taken by unknown, (B) was taken by Grant P. Elliott in 2002, and (C) was taken during 2019.
Source: United States Geological Survey Photographic Library, Denver, CO.

Fig 15. Photo site 2. View is to the southwest looking up into Uncompahgre Peak surrounding area. Note the area of beetle kill within the surrounding spruce-fir forest to the east of the mountain.

Fig 16. Photo site 2. View is to the southeast looking up into Uncompahgre Peak surrounding area. Note the area of beetle kill within the surrounding spruce-fir forest to the east of the mountain.

Fig 17. Photo site 2. View is further east of Uncompahgre Peak. Note the area of beetle kill within the surrounding spruce-fir forest to further east of the mountain

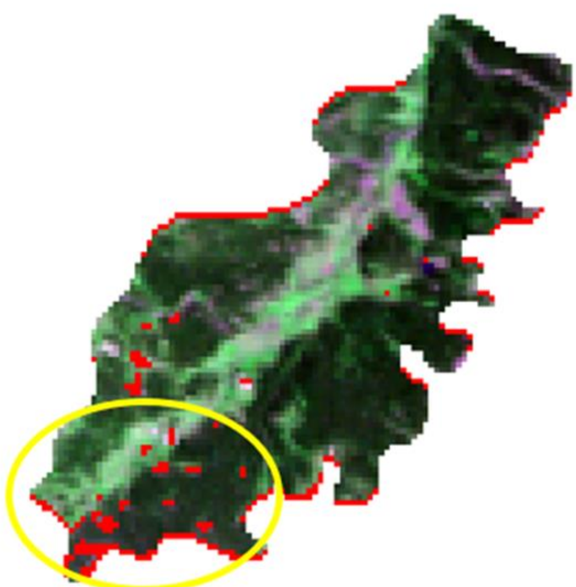

Fig 18. 2003/2011 Change detection of Uncompaghre Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Note the majority of the pixel change represented in red is primarily located within the lower portion of the scene in areas dominated by spruce-fir forest

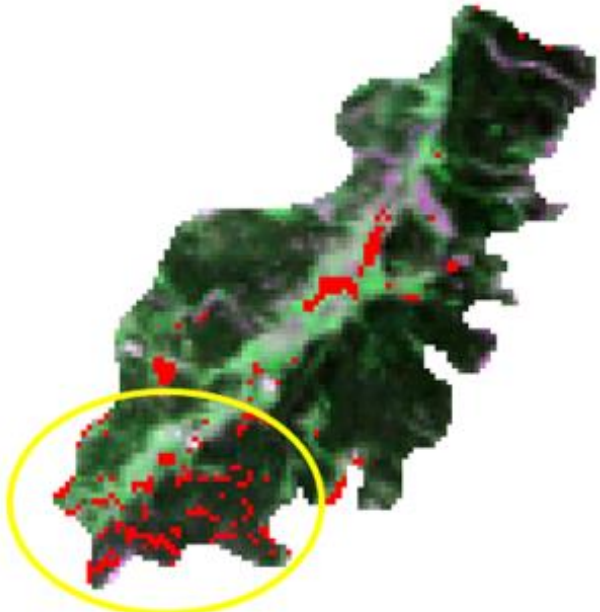

Fig 19. 2011/2019 Change detection of Uncompaghre Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Note the majority of the pixel change represented in red has increased within the lower portion of the scene where it was previously seen while also being witnessed within the upper portion of the scene.

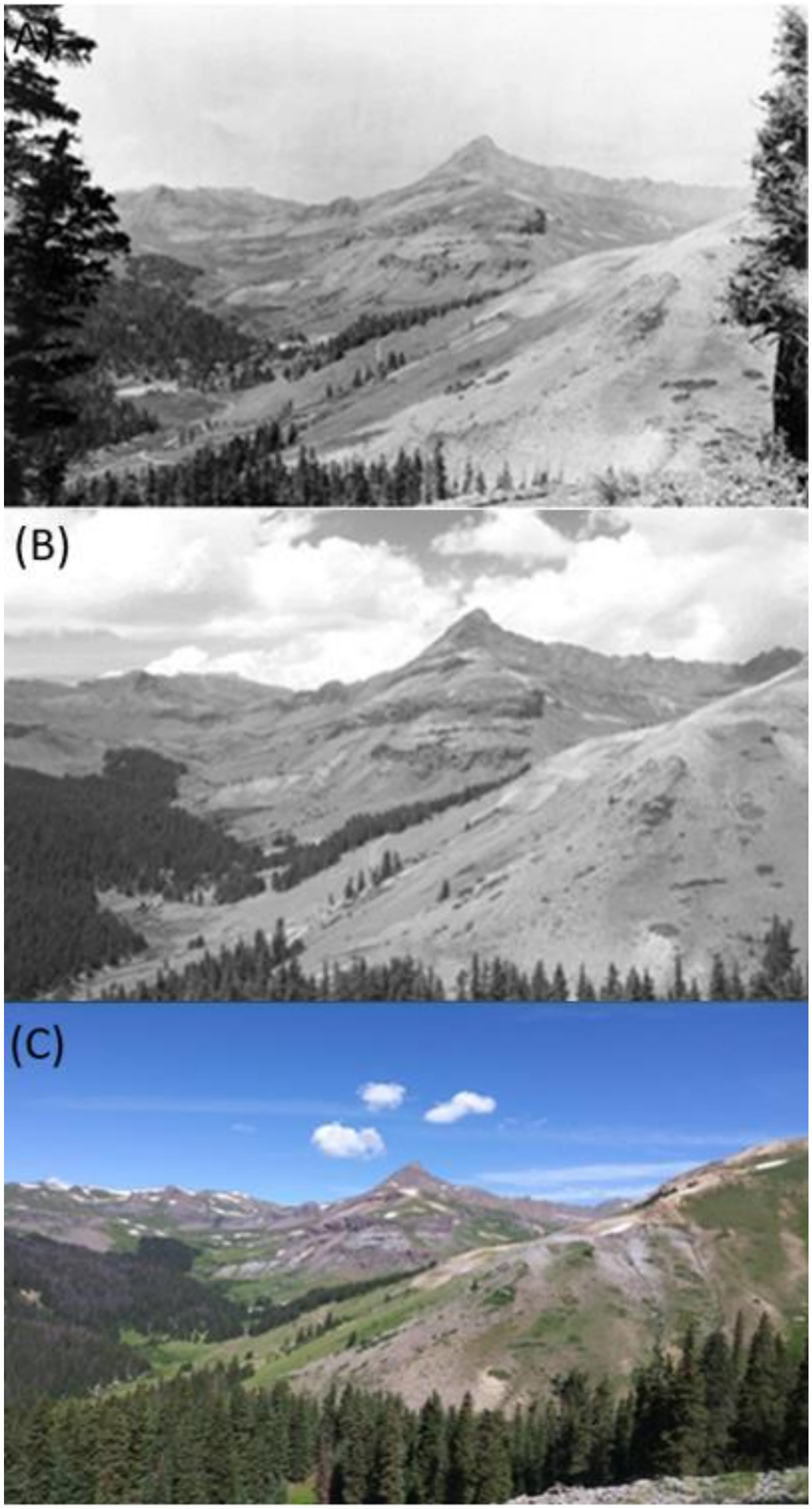

Fig 20. Photo site 3. View is to the southelooking up into Wetterhorn Peak. The original photo (A) was taken by Cross, W. in 1905, (B) was taken by Grant P. Elliott in 2002, and (C) was taken during 2019.
Source: United States Geological Survey Photographic Library, Denver, CO.

Fig 21. 2003/2011 Change detection of Wettterhorn Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Note the majority of the pixel change represented in red is primarily located within the left-hand portion of the scene in areas dominated by spruce-fir forest as well as pockets in the right-hand portion.

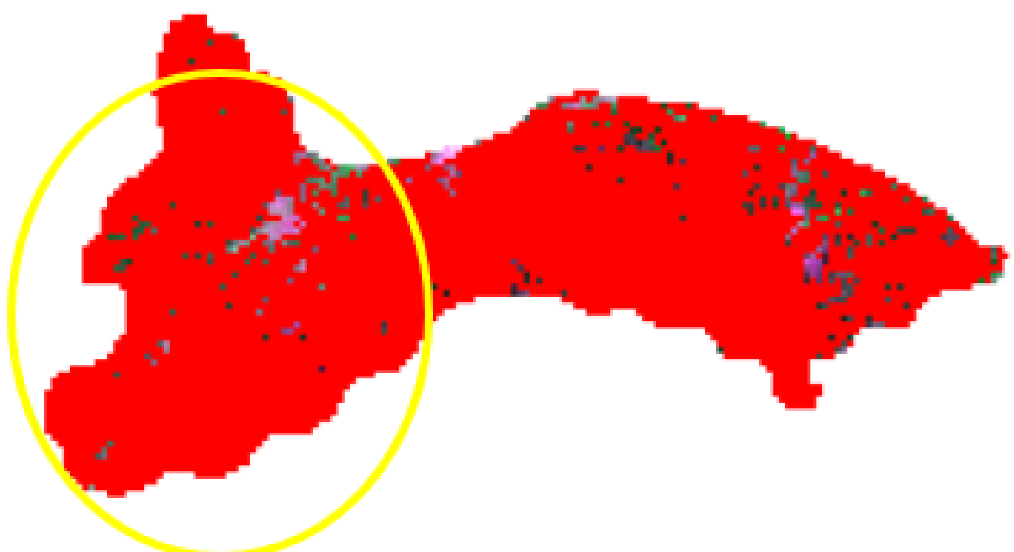

Fig 22. 2011/2019 Change detection of Wettterhorn Peak location coinciding with area of witnessed spruce beetle kill during the summer of 2019. Note almost all of the scene is represented in red indicative of pixel change with a few pockets having not seen change

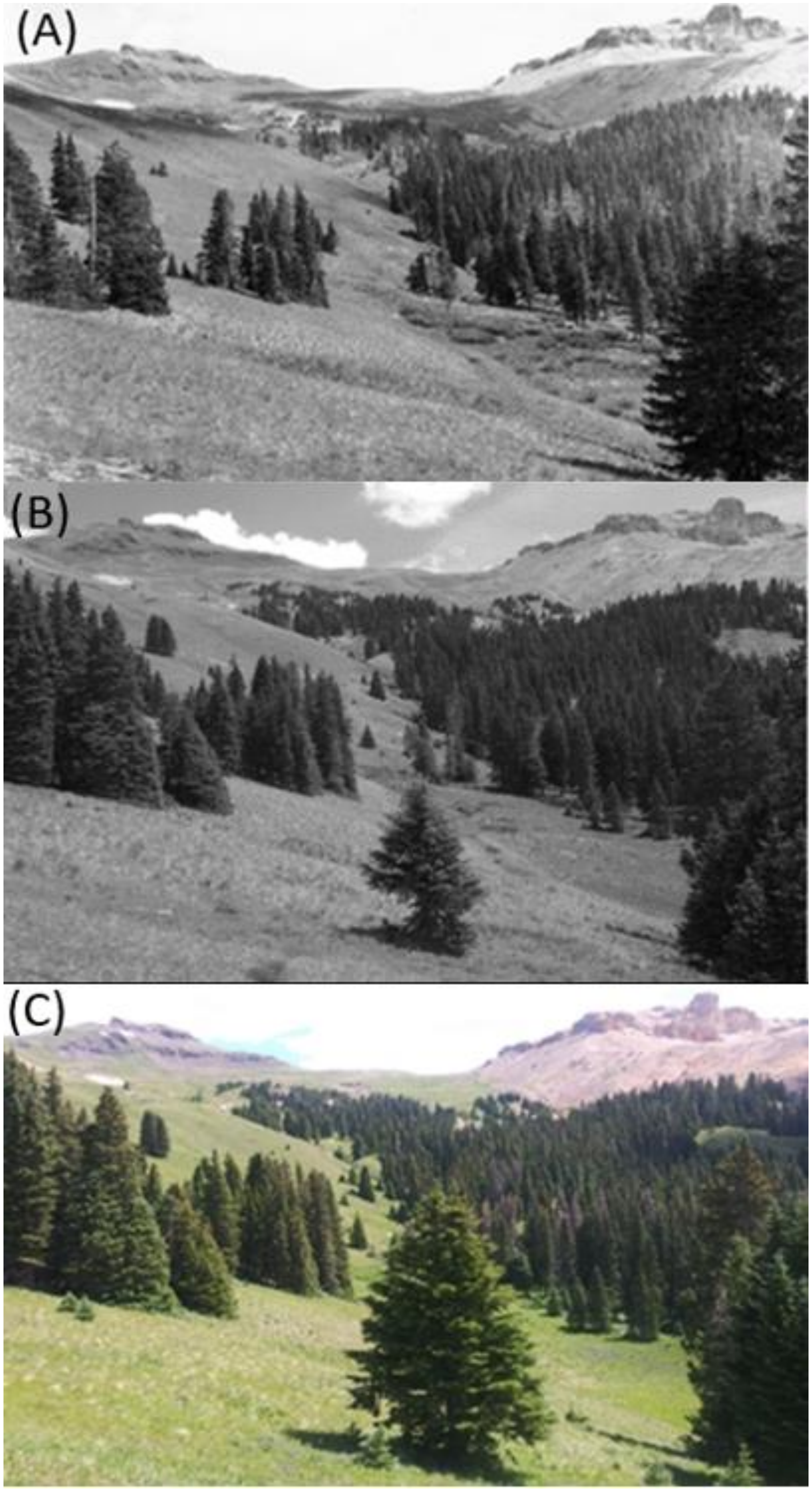

Fig 23. Photo site 3. View is to the northwest looking up into Broken Hill. The original photo (A) was taken by Cross, W. in 1905, (B) was taken by Grant P. Elliott in 2002 and (C) was taken during 2019.
Source: United States Geological Survey Photographic Library, Denver, CO.

New #	Orig. Photographer	Original Year	Elevation ft	Elevation m	Slope Aspect (°)	Description
1	Jackson, W.H.	1875	10589	3227.5	125 SE	Borens Gulch
2	Cross, W.	1896	11827	3604.9	55 NE	Mount. Hesperus
3	Jackson, W.H.	Unknown	12732	3880.7	85 E	Uncompahgre Peak
4	Cross, W.	1905	11860	3614.9	90 E	Wetterhorn Peak
5	Cross, W.	1905	11626	3543.6	310 NW	Broken Hill

Table 1. Historical photographs in addition to the 2002 repeat photography study retaken during the Summer of 2019. The elevation and slope aspect refer to the photo point.

	Changes that Occurred	
Site Name	**Beetle Kill**	**Increased Establishment**
Boren's Gulch		**X**
Mount Hesperus		**X**
Uncompahgre Peak	**X**	**X**
Wetterhorn Peak	**X**	
Broken Hill	**X**	**X**

Table 2. Results of 2019 repeat photography study taken during the Summer of 2019. The elevation and slope aspect refer to the photo point