Treeline Monitoring in the San Juan Mountains

Michelle Fink, Renée Rondeau, and Karin Decker
Colorado Natural Heritage Program

December, 2014

Renée Rondeau measuring treeline on Kendall Mountain in 2012. Photo by Gordon Rodda.

NATURAL HERITAGE PROGRAM
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CONTENTS

EXECUTIVE SUMMARY

Temperatures in the San Juan Mountain region have risen approximately 1.8°F over the last 30 years, primarily after 1990, and are projected to continue warming. As temperatures rise we expect increased rates of tree growth and tree establishment at the subalpine/alpine ecotone ("treeline"). We wanted to discern if upper treeline changes could already be detected through remote sensing. We compared aerial photographs from 1951 and 2011 for 8 San Juan mountain peaks. The images were georeferenced and virtual transects were created to help establish position of treeline in each sample year. We found that the treeline has not moved, but that tree density has increased. Therefore, the difference between 1951 and 2011 treeline was calculated by determining differences in tree density within the area delimited as treeline. Differences in shadows between images were corrected for by examining shadows of immutable objects and calculating a correction factor. Detected differences varied widely, from 2 - 27% increase in tree density (mean 12%) over the last 60 years. We conclude that treeline changes can be detected, although the rate of change is slow and variable. The high variability may be due to aspect, with the wetter aspects increasing faster. We also suggest that this cost-effective remote sensing technique could be a useful monitoring tool for determining landscape changes in areas that are hard to access.

ACKNOWLEDGEMENTS

This project was funded through the Tres Rios office of BLM with assistance from Gretchen Fitzgerald at the San Juan National Forest. Special thanks to Chris Landry at the Colorado Snow and Avalanche Studies for assisting with weather data and permission to use their repeat photos.

INTRODUCTION

The division between treeless alpine habitats and adjacent forests is generally acknowledged to be an ecotonal transition zone, and the treeline itself is difficult, if not impossible, to locate on the ground (Körner 2012). What appears at a distance to be a well-defined treeline is typically a mixed zone of closed forest patches, isolated seedling trees, dwarfed trees, and open herbaceous- or rock-covered ground when viewed in situ. In spite of the difficulty of locating treeline with precision, the phenomenon of a high elevation (or high latitude) limit to the growth of trees, and the tendency of treeline elevation to decrease with increasing latitude north or south of the equator has long been recognized (Daubenmire 1954). The causes and variety of high elevation (alpine) North American treeline have been the subject of ongoing debate since at least the latter years of the 19th century when Gannett (1899) described the timber line in the U.S. south of Canada. Theories to account for treeline have included a variety of mechanisms such as direct stress on the tree (e.g., freezing or desiccation of plant tissues freezing), disturbance (e.g., mechanical damage by wind or avalanche), limitations on reproduction, a carbon balance incapable of maintaining the tree, or other growth limitation (Körner 1998).

Treeline-controlling factors operate at different scales, ranging from the microsite to the continental (Holtmeier and Broll 2005). On a global or continental scale, there is general agreement that summer temperature is a primary determinant of treeline. Körner (2012) attributes the dominance of thermal factors at this scale to the relative consistency of atmospheric conditions over large areas, especially in comparison to more local influence of soil and moisture factors. Furthermore, there appears to be a critical duration of summer temperatures adequate for the growth of trees in particular. Prentice et al. (1992) found that alpine treeline is not determined by winter temperatures but rather by summer temperatures that support growth (e.g. treeline corresponds closely to areas with fewer than 350 growing degree days, 5° C base). In other words, the short growing season and cool summers associated with alpine limits tree establishment and growth. At more local scales, soil properties, slope, aspect, topography, and their effect on moisture availability, in combination with disturbances such as avalanche, grazing, fire, pests, disease, and human impacts all contribute to the formation of treeline (Richardson and Friedland 2009, Körner 2012). Patterns of snow depth and duration, wind, insolation, vegetation cover, and the autecological tolerances of each tree species influence the establishment and survival of individuals within the treeline ecotone (Moir et al. 2003, Holtmeier and Broll 2005, Smith et al. 2009).

The current location of treeline is a result of the operation of climatic and site-specific influences over the past several hundred years, and does not exactly reflect the current climate (Körner 2012). The treeline position lag time behind climate change is estimated to be 50-100+ years, due to the rarity of recruitment events, the slow growth and frequent setbacks for trees in the ecotone, and competition with already established alpine vegetation (Körner 2012). Nevertheless, on the basis of historic evidence, treeline is generally expected to migrate to higher elevations as temperatures warm, as permitted by local microsite conditions (Smith et al. 2009, Richardson and Friedland 2009, Grafius et al. 2012). The gradual advance of treeline is also likely to depend on precipitation patterns. Seedling establishment and survival are greatly affected by the balance of snow accumulation and snowmelt. Soil moisture, largely provided by snowmelt, is crucial for seed germination and survival. Although snowpack insulates seedlings and shields small trees from wind desiccation, its persistence shortens the growing season and can reduce recruitment (Rochefort et al. 1994).

Global carbon dioxide levels have reached 400 ppm, an increase of 40% over the pre-industrial era, due primarily to the burning of fossil fuels. In combination with the dramatic increase of other greenhouse gases such as methane and nitrous oxide, this anthropogenic forcing has added significant heat to our climate system (Lukas et al. 2014). Colorado temperatures, including high elevations, have risen approximately 2° F (1.1° C) since 1980 (Lukas et al. 2014). In the San Juan Mountain region, Rangwala and Miller (2010) reported a 1.8° F (1° C) increase, primarily between the years 1990-2005. Summer temperatures increased slightly more than winter temperatures. While upward tree migration is expected with increased temperature, we are less clear on the rate and place where this is most likely to occur. Our 2012 pilot project (Rondeau et al. 2012) found that Krummholz trees on Kendall Mountain had new vertical growth, were setting seed, and were generally losing their Krummholz form. In addition, we also documented an increased growth rate (larger annual rings) beginning around 1996 (Figure 1). This increased growth rate was strongly correlated with an increase in growing degree days, i.e., a warmer and longer growing season. While bolting Krummholz and increased growth rate are good indicators that a warming climate is positively affecting upper elevation trees, they are not the same as treeline movement.

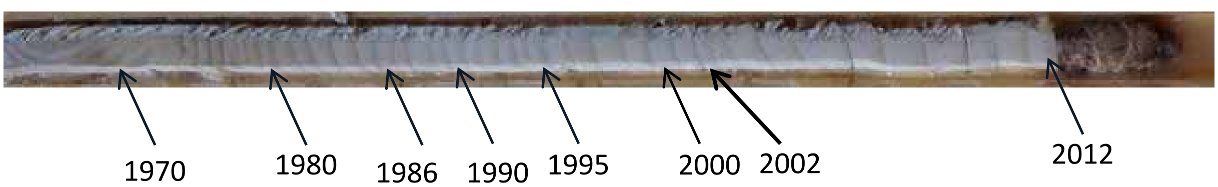

Figure 1. Tree core from Kendall Mountain treeline, showing increasing growth rate after 1995 (Rondeau et al. 2012).

In order to determine if the San Juan Mountains have already experienced some treeline movement, we conducted a remote sensing analysis comparing historic to current photos that include different aspects on several mountains in the northern San Juan Mountain Range.

METHODS

Nine mountain peaks within the Bureau of Land Management's Tres Rios Field Office Resource Management Area were examined and a treeline change analysis was done on eight; Dome Mountain, Eureka Mountain, Lone Cone, Macomber Mountain, Storm Peak, Sugarloaf Mountain, and Treasure Mountain (Figure 2). The ninth, King Solomon Mountain, was determined to be too constrained by bare rock to show any difference in treeline position or density over time. Peaks were chosen based on the visual discreteness of their treelines. Varying slope aspects were selected to mitigate for any aspect bias.

Scanned aerial single-frame photos from a flight in September 1951 (USGS 1951) were compared to digital composite 1 m imagery from 2011 (USDA 2011). Due to its distance from the other peaks, Lone Cone was not covered in the 1951 flight, and so a photo from June 1952 was used instead (USGS 1952; wherever "1951" is used hereafter, know that for Lone Cone it was 1952). Neither the 1951 nor the 2011 images were post-processed to correct for distortion, though the level of lens and angle distortion is much higher in the 1951 photos. This resulted in highly complex and imperfect georeferencing of the 1951 images to spatially match them to the 2011 one. The 1951 images were georeferenced to the 2011 image using the spline algorithm in ESRI ArcGIS Desktop 10.0 (ESRI 2010) with between 26 - 63 reference points per image. Recognizable, immovable landmarks (primarily boulders and exposed bedrock) were used as reference points. The georeferenced 1951 photos were then converted to ESRI raster, 1 m resolution, and snapped to the 2011 imagery.

To identify treeline, each image underwent a 10 m focal mean smoothing and then reclassified as either "tree/shadow" or "not tree/shadow" (shadows being largely indistinguishable from the trees that cast them). The reclassification cut-off value was initially chosen via a Jenks Natural Breaks classification, but then adjusted by visually reviewing how well trees were represented in each case.

Virtual transects were radiated from each peak (or local highpoint, as appropriate) in either 2.5 or 5 degree increments, depending on the distance from the transect origin to the treeline. In this way, all transects travel downhill through the treeline. A point was hand placed along each transect where it first intersected areas identified as "tree/shadow" for each time period. These points were then connected into lines representing the treeline at 1951 and 2011. The amount, in square meters, of "tree/shadow" in the area between the 1951 and 2011 treelines was calculated for each year (Figure 3).

The differences between shadow shape, location, and size in the two images varied because of remaining image distortion and differences in time of year and time of day the photographs were taken. To ensure that measured tree densities were not unduly influenced by this, shadow differences were measured by digitizing the shapes of distinct shadows cast by recognizable rocks in the two images. As many useable rock shadows as could be located close to the treeline were measured. Most slopes had 6-8, but Lone Cone only had 1. A shadow correction factor was then applied to each "tree/shadow" amount by multiplying it by the percent overlap of the 1951 and 2011 shadows (Table 1).

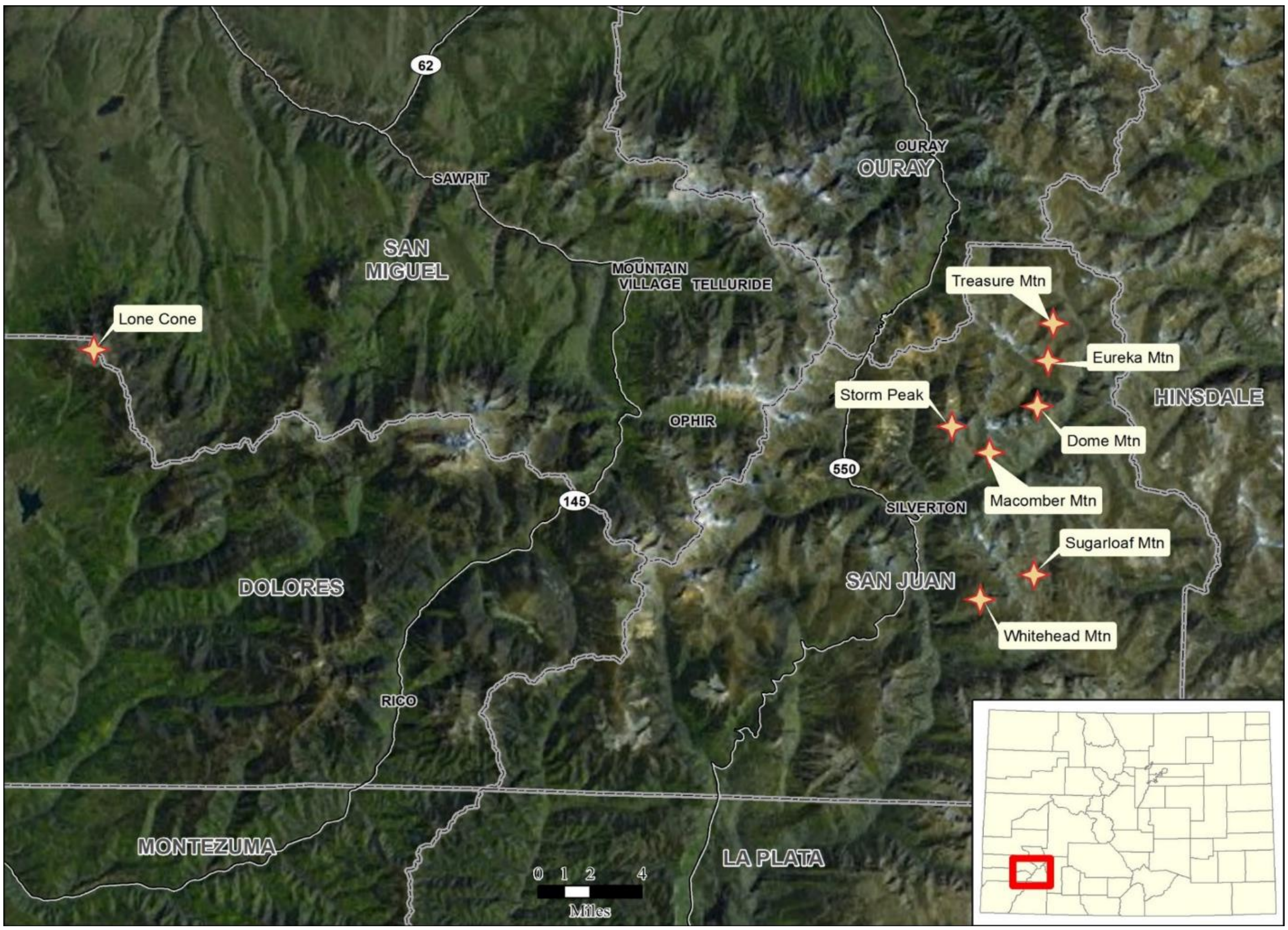

Figure 2. Location of peaks used in analysis.

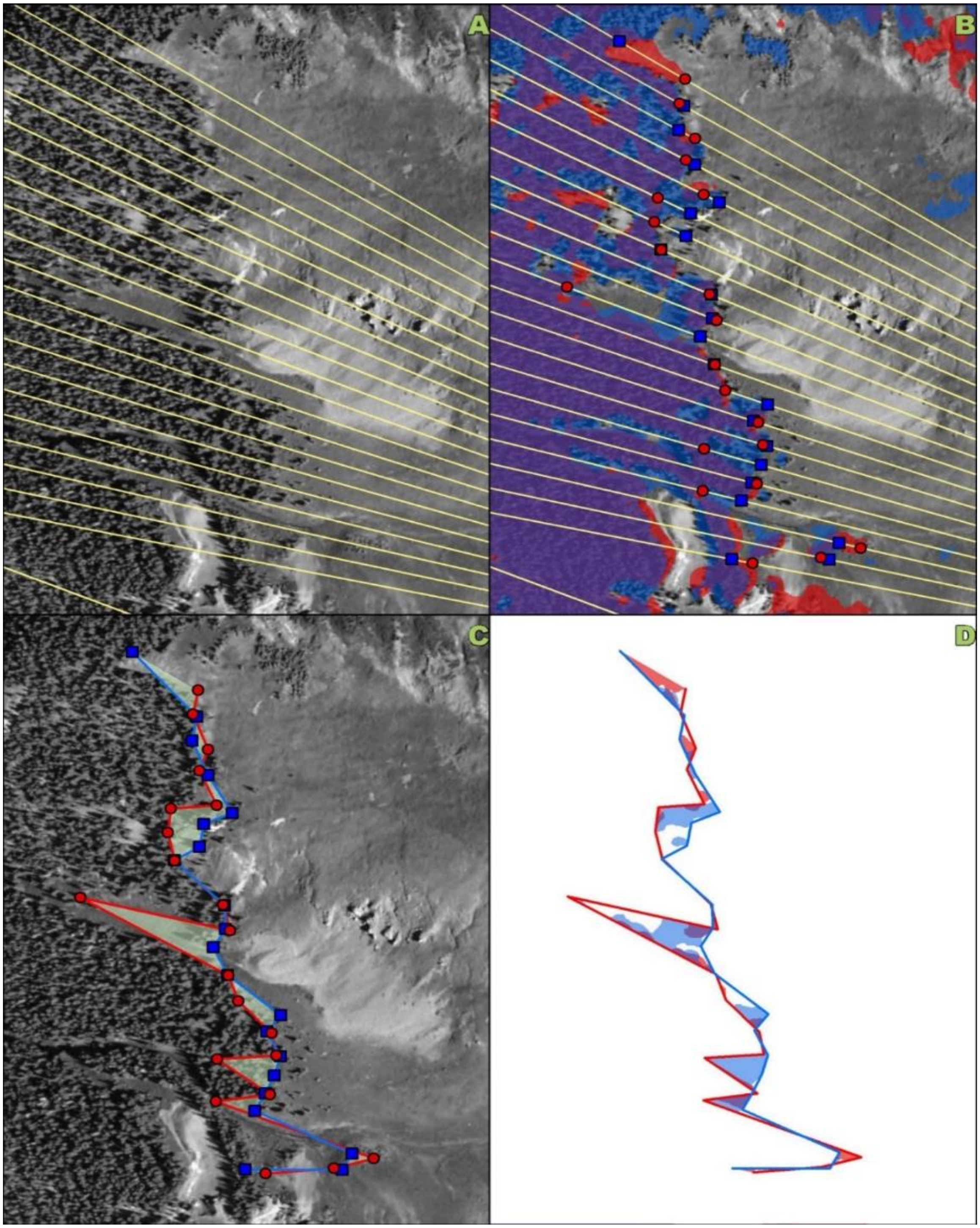

Figure 3. Treeline analysis example. (A) Transects laid over 2011 image. (B) 1951 (red) and 2011 (blue) tree/shadow and placement of points. Purple is where the blue and red overlap. (C) Creation of 1951 (red) and 2011 (blue) treelines, and the area between the two (light green). (D) Amount of tree/shadow in the area between treelines for each year.

Table 1. Example of shadow correction applied to measured tree/shadow density (from Macomber Mtn data).

	Rock Shadows (m^2)		
Rock	**1951**	**2011**	**overlap**
1	80.4	88.2	61.2
2	265.3	377.3	225.5
3	48.2	120.6	13.1
4	115.2	135.1	50.8
5	55.6	68.8	9.7
6	167.2	110.9	51.1
7	85.7	103.0	34.1
8	971.7	1,386.3	729.7
Totals	1,789.3	2,390.2	1,175.2
Shadow correction factor:			
[overlap Total] / [1951 Total]			66%
[overlap Total] / [2011 Total]			49%
Corrected tree density:			**m^2**
Total area between treelines			207,070
Raw 1951 "tree/shadow"			14,966
Corrected 1951 ([raw] * 0.66)			9,829
1951 tree density			5%
Raw 2011 "tree/shadow"			31,749
Corrected 2011 ([raw] * 0.49)			15,610
2011 tree density			8%

RESULTS

Because of the large size of the Storm Peak treeline, it was separated into north-, west-, and south-facing slopes and treeline change was calculated separately for each. The treeline on the south-facing slope of Storm Peak had such a large difference in light reflectance values between the 1951 and 2011 images that there was no way to calculate any real change. This slope was therefore removed from the summary analysis. Table 2 and Figure 4 show the results of the remaining treeline analyses.

Table 2. Percent increase in tree density at treeline.

Peak	Aspect	60 yr change
	N-facing	27%
Storm Peak	W-facing	14%
Dome Mountain	NW-facing	19%
Eureka Mountain	N-facing	2%
Lone Cone	E & S facing	2%
Macomber Mountain	SE-facing	3%
Sugarloaf Mountain	NE-facing	15%
Treasure Mountain	N & E facing	24%
Whitehead Mountain	NW-facing	6%

Detected changes varied widely by peak, ranging from 2% - 27%. The mean change is 12% with a standard deviation of 10%. However, the sample size (9 slopes) is very small, making the standard deviation of questionable relevance.

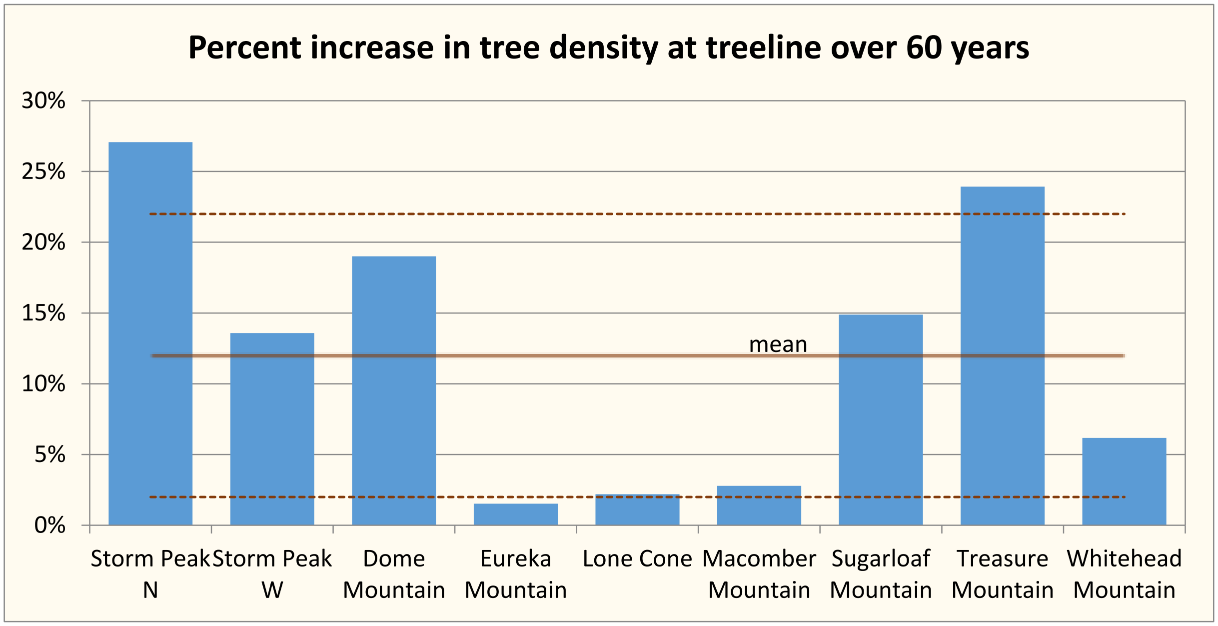

Figure 4. Results of treeline analysis. The dotted lines are ± 1 standard deviation from the mean.

The tree density change and general aspect of each slope were graphed (Figure 5) to see if any aspect trend could be seen. The graph may imply possible greater change on slopes that are not South-facing but, again, low sample size and high variation obscure any trend in aspect that may exist.

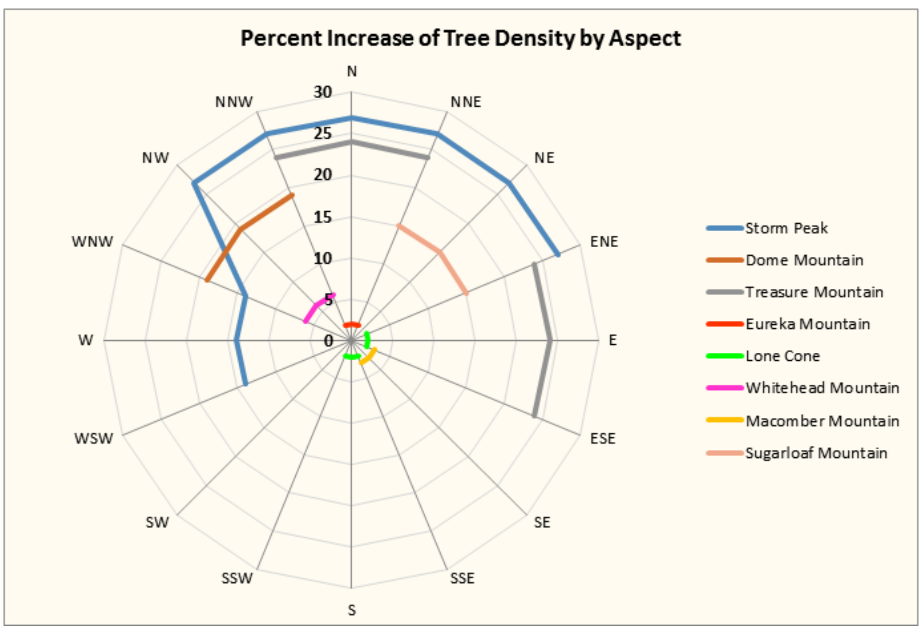

Figure 5. Results graphed by general aspect.

DISCUSSION

Many of the San Juan region ecosystems are vulnerable to being lost or severely degraded by 2100, due to projected changes in Colorado's climate. The alpine ecosystem is considered one of the most vulnerable (Decker and Rondeau, 2014). One of the expected changes to the alpine zone is a "new" vegetation structure. The current forb and grass composition are likely to be replaced by trees and shrubs, thereby altering Colorado's iconic alpine system and its unique flora and fauna. The subalpine/alpine zone is also very important for rare plants which may be impacted by a change in structure (Handwerk et al., 2014). Managers can benefit by understanding the rate of change and where the change is most likely to occur. In addition, detecting and monitoring change is essential for managers and management decisions. The most cost-effective monitoring tool has a better chance of long-term implementation. This study supports the use of remote sensing as a cost-effective tool for detecting changes in treeline.

Our remote sensing analysis of 8 mountains suggest that change is already evident, albeit the rate of change is slow and highly variable. Most of the evidence points to tree density increasing at or near treeline, rather than a clear upward advancement of treeline. It is much more likely that a seedling will establish near a parent plant than it is for a seedling to become established a great distance from the parent, particularly uphill. Thus treeline movement may start with in-filling prior to moving notable distances up the slope. Other site-specific factors can control treeline change, such as soil depth and degree of slope. North-facing slopes may create a wetter environment that benefits seedling establishment. While our sample size is too low to confidently state that aspect makes a difference we did note that the largest increase in treeline density was calculated on the north-facing slope of Storm Peak (27%), while the west-facing slope of Storm Peak had a 14% increase. Our 2012 pilot project (Rondeau et al., 2012) occurred on a predominately south-facing slope on Kendell Mountain. Our ground-truth part of the pilot project found the most obvious changes in a small drainage with a northerly aspect (Figure 6). A nearby subalpine-alpine vegetation monitoring study supports our findings. In 2014, the Colorado Snow and Avalanche Studies repeated their study of Senator Beck basin (Lyon et al., *in prep.*). A preliminary analysis of the 2004-2014 repeat photos from the study depicts a changing subalpine zone. This is most evident on the north-facing slopes where Krummholz trees have bolted and shrubs have expanded. Figure 7 provides an example of the repeat photos.

Over the years, there has been research into the potentially positive effects of increased carbon dioxide (CO_2) levels on plants, with some indication of highest benefit to trees (Ainsworth and Long, 2005). Although increased CO_2 levels can benefit the growth of virtually any plant, the effects of drought, heat stress, competition, disease, and nutrient limitations are likely to confound any effect (Ainsworth and Long 2005, Zhao and Running 2010, Larsen et al. 2011).

We conclude that changes are already occurring at the upper treeline area and that the 1.8°F increase in temperature since 1990 is the most likely major contributing factor. Different aspects may respond at a different rate, but more sample sites are required before this can be stated with certainty.

Remote sensing has its limitations, however the ability to quickly and cost-effectively discern changes in treeline in areas that are otherwise difficult to access makes this type of analysis an excellent tool for landscape monitoring. On-the-ground monitoring sites could be prioritized from this type of analysis.

Figure 6. A cohort of younger trees just above "treeline" on Kendall Mountain. The more northerly aspect has more trees than the southerly aspect.

Figure 7. A north-facing slope at 12,100 feet elevation in Senator Beck Basin, near Storm Peak. The upper photo was taken on July 7, 2004 while the lower photo was taken on July 21, 2014. In ten years the tree height and shrub density visibly increased and Krummholz bolting was quite evident. Top photo taken by Peggy Lyon, bottom by Renée Rondeau.

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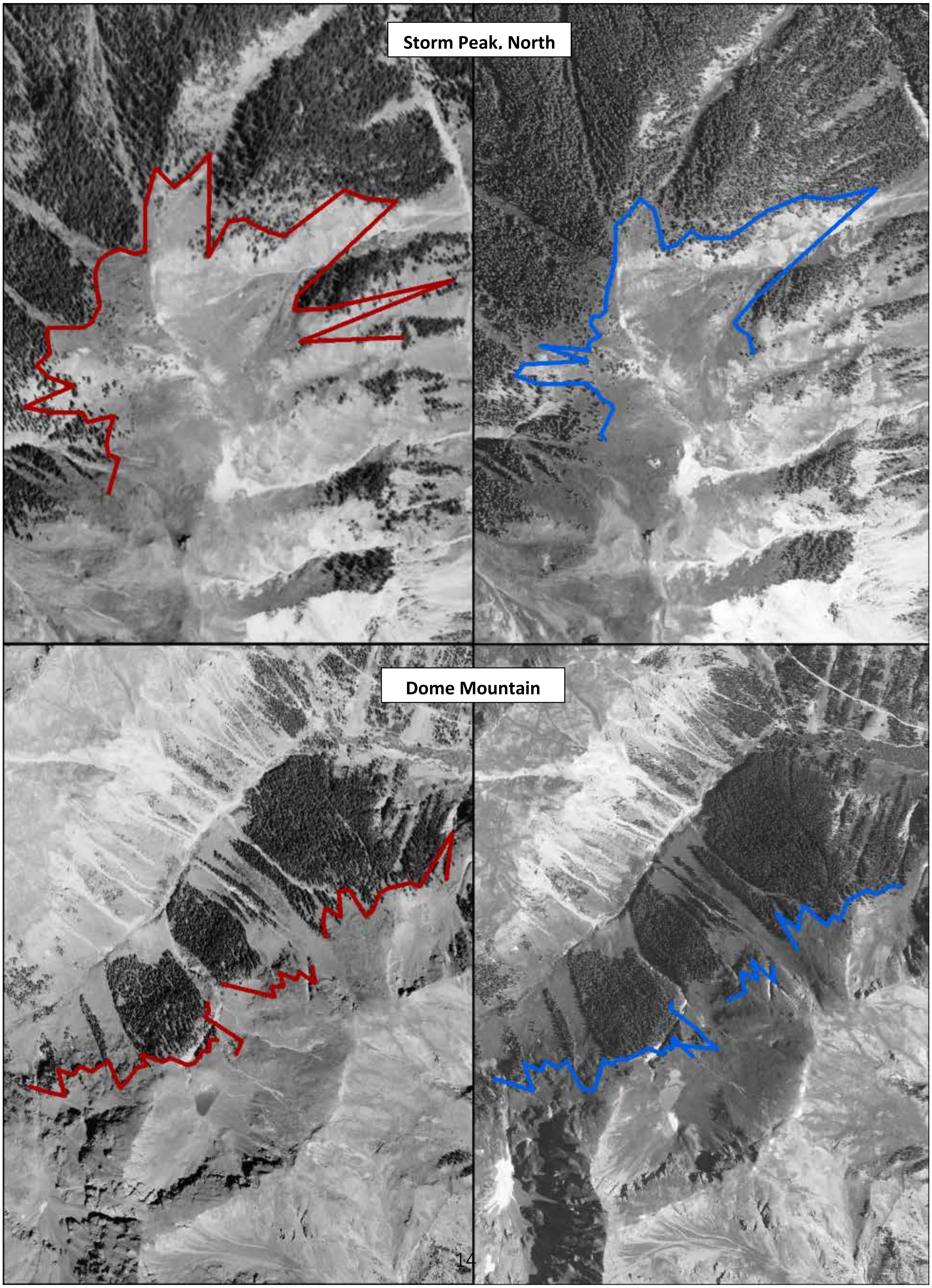
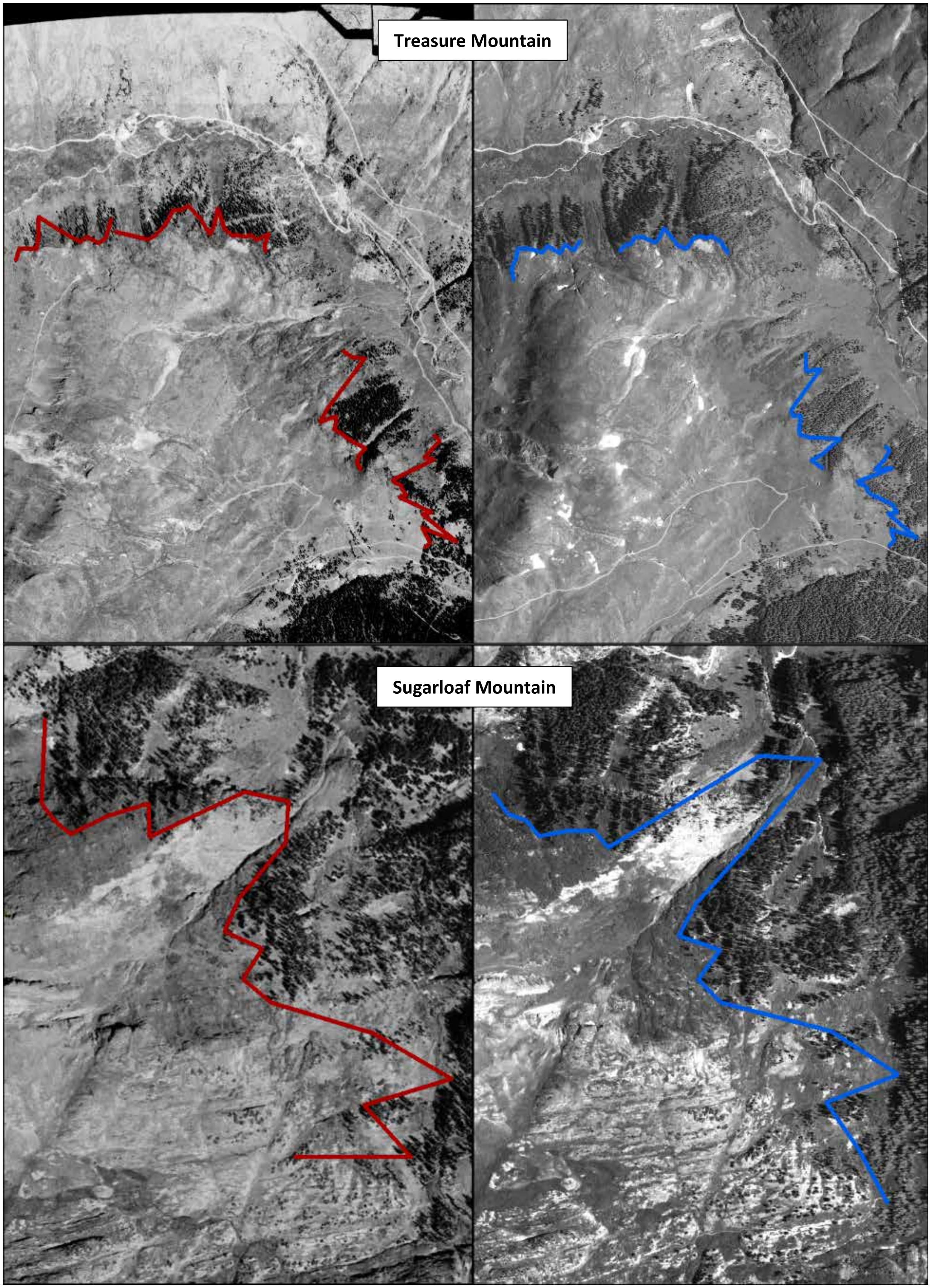
APPENDIX A

Selection of 1951 and 2011 aerial photos used for the analysis. 1951 on the left and 2011 on the right, with their respective treelines demarcated.




Treasure Mountain
Sugarloaf Mountain