THESIS

# CHANGE IN PIÑON-JUNIPER WOODLAND COVER SINCE EURO-AMERICAN SETTLEMENT: EXPANSION VERSUS CONTRACTION ASSOCIATED WITH SOIL PROPERTIES

Submitted by

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ABSTRACT

CHANGE IN PIÑON-JUNIPER WOODLAND COVER SINCE EURO-AMERICAN SETTLEMENT: EXPANSION VERSUS CONTRACTION ASSOCIATED WITH SOIL PROPERTIES

Woodland and forest ecosystems across western North America have experienced increased density and expansion since the early 1900s, including in the widely distributed piñon-juniper vegetation type of the U.S. Southwest. Fire suppression and grazing are often cited as the main drivers of these historic changes and have led to extensive tree-reduction treatments across the region. However, much of the scientific literature on piñon-juniper expansion dates back only to the early 1900s, which is generally a half a century after Euro-American settlement. This study uses General Land Office (GLO) surveys to establish piñon-juniper woodland extent in the late 19th century at the incipient stages of Euro-American settlement in southeastern Colorado and compares this data with 2017 aerial imagery of woodland cover. We found substantial amounts of woodland contraction as well as expansion: approximately 61% of historically dense woodland is now savanna or open (treeless) whereas approximately 57% of historically open areas are now savannas or woodlands, although analyses at finer spatial scales suggest considerably more contraction relative to expansion. We assessed change in woodland cover and extent as a function of soil type, a dominant biophysical control, and found that the highest rates of expansion occurred upon shallow, rocky soil types with low soil available water capacity (AWC). These low soil AWC areas support little herbaceous vegetation and thus had less grazing pressure and were unlikely to carry frequent surface fires historically, suggesting that fire suppression and grazing were not the primary drivers of expansion. Meanwhile, the significant contractions in woodland extent occurred on deeper, upland soils with higher soil AWC, which support greater herbaceous cover and were likely where early settlement and treecutting was prevalent. Our results provide mixed support for the often widespread assumption of woodland expansion since Euro-American settlement and suggest that the expansion that has occurred in our study area is unlikely a result of past grazing or fire suppression. This paper uses important, underutilized sources of ecological data in order to more directly assess the earliest effects of Euro-American settlement on one of the U.S. Southwest's most prevalent and important vegetation types.

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**Introduction**

Woodland and forest ecosystems across western North America have expanded and thickened since the early 1900s due to a suite of factors that signify both natural and unnatural change. Natural factors include increased tree recruitment during climatically favorable (cool and wet) periods (Barger et al., 2009; Shinneman & Baker, 2009), recovery following natural disturbances that occurred in the 19$^{th}$ century (Miller et al., 2008), and an overall expansion of many tree species ranges across the West due to the steady, ongoing climatic emergence from the last Ice Age (Clark, 1998; Hewitt, 1996; Johansen & Latta, 2003). Since Euro-American settlement, dramatic changes in land use have initiated more unnatural pressures on tree species ranges through grazing, fire exclusion, and woodcutting. This has been documented to occur in many areas dominated by piñon (*Pinus edulis; P. monophylla*) and juniper (*Juniperus osteosperma; J. monosperma*) woodlands, a widespread vegetation type in the U.S. Southwest (Johnsen, 1962; Jacobs et al., 2008; Romme et al., 2009).

The majority of scientific literature documents piñon-juniper expansion from the early 1900s onwards (Johnsen, 1962; Belsky, 1996; Miller & Rose; 1999; Miller et al., 2008; Romme et al., 2009), often concluding that these woodlands are unnaturally dense and widespread. However, Euro-American influence on these ecosystems has existed since settlement and natural resource exploitation began in the U.S. Southwest in the mid to late 19$^{th}$ century (Evans, 1988), so observed expansion in the 1900s could be recovery from earlier woodcutting. Across the semi-arid U.S. Southwest, piñon-juniper woodlands often represented the primary source of fuel and structural wood for homesteaders and new mining operations. Homesteaders would cut down large amounts of piñon and juniper timber for fence posts, housing, and fire wood for winter (Evans, 1988). Moreover, 19$^{th}$ century mining operations in piñon-juniper ecosystems exerted even greater pressure upon these ecosystems, often involving the removal of vast swaths of woodland. In Arizona and Nevada in the 19$^{th}$ century, mining operations resulted in the clearcutting of large areas of piñon-juniper woodland in order to provide charcoal for steam power to run machinery (Bahre & Hutchinson, 1985; Ko et al., 2011). Since much of the expansion literature dates only to the early 20$^{th}$ century, it is important to gather data from the initial time of Euro-American settlement when woodcutting quickly became an ecologically significant activity in piñon-juniper woodlands. The present study uses data from the late 19$^{th}$ century at the incipient stages of human development and fuelwood usage in order to assess the degree of expansion and contraction that has occurred since Euro-American settlement.

Whereas initial logging and woodcutting in the mid to late 1800s in piñon-juniper ecosystems may have reduced woodland density and extent, fire suppression and grazing beginning in the 19$^{th}$ century may have contributed to the densification and expansion of piñon-juniper woodlands. Piñon-juniper woodlands are often characterized by an infrequent, high-severity fire regime (>250 year recurrence), such that fire exclusion in these situations does not significantly influence tree cover (Floyd et al., 2004; Huffman et al., 2008; Shinneman & Baker, 2009). However, piñon-juniper ecosystems that are more savanna-like in nature, and dominated by a heavy grass component, can carry surface fire much easier, resulting in more frequent, low severity fires on a decadal time scale (Miller & Tausch, 2001; Miller et al., 2008; Romme et al., 2009). Consequently, fire exclusion in these savanna-like landscapes would likely result in an increase in tree seedling survival where they would otherwise be culled by frequent surface fires. Further, there may be a positive feedback in these savanna-like piñon-juniper ecosystems whereby as these ecosystems become more dense due to fire suppression, there is a corresponding decrease in fire frequency due to reduced surface fuels to carry fire (Margolis, 2014). Human land use change since the 19th century may have also increased piñon-juniper seedling recruitment through grazing of domestic ungulates. Piñon-juniper ecosystems exist in semi-arid, and thus water-limited environments. Consequently, interspecific competition between tree seedlings and herbaceous understory plants have been hypothesized to limit the amount of trees that can establish and persist at the piñon-juniper-rangeland ecotone (Chambers et al., 1999). Indeed, Redmond et al (2018) found reduced tree recruitment in areas of high grass cover. Grazing reduces the density and cover of the herbaceous layer, thus resulting in reduced tree seedling competition and an increased likelihood of woodland expansion and infilling (Johnsen, 1962; Bachelet et al., 2000; Gascho Landis & Bailey, 2005). Grazing and fire exclusion are two important factors of human land use change since Euro-American settlement that may have increased piñon-juniper cover and density in areas with high herbaceous cover and that historically carried surface fires.

The effects of fire exclusion and grazing in piñon-juniper woodlands likely varies due to the soil properties in a specific area. The occurrence of woodland and savanna piñon-juniper ecosystems is closely correlated with differences in soil type (Romme et al., 2009). Savanna and grassland ecosystems tend to be dominated by deep, fine-textured soils while woodland environments are often relegated to shallow, rocky, or coarse-textured soils (Gascho Landis & Bailey, 2005; Romme et al., 2003; Miller et al., 2008). Since soil type has a large influence on herbaceous vegetation, it can be a robust predictor of the historic fire regime and consequently areas where piñons and junipers are most likely to infill and expand. As a result, we would expect to see the greatest levels of expansion and thickening of woodlands in areas where soils support greater levels of herbaceous vegetation such that they would have historically carried frequent surface fire prior to the introduction of fire suppression and livestock grazing.

The expansion of piñon-juniper woodlands is often attributed to the more unnatural drivers of fire suppression and grazing, leading to widespread treatments across the western U.S. (Redmond et al., 2014; Romme et al., 2003). However, there are also natural reasons why piñon-juniper woodlands may have expanded, such as a response to cool and wet climate pulses (Barger et al., 2009; Shinneman & Baker, 2009) or due to recovery from past disturbances, including woodcutting (Bahre & Hutchinson, 1985; Evans, 1988; Miller et al., 2008; Ko et al., 2011). A key first step in order to determine whether piñon-juniper woodlands are unnaturally dense is to document changes in tree cover since the earliest stages of Euro-American settlement.

This paper aims to assess the degree of expansion and contraction of piñon-juniper woodlands in the late 19th century and how that varies depending upon soil type. Utilizing the first General Land Office (henceforth referred to as 'GLO') surveys of southeastern Colorado from the late 19th century, we first determine the historic (1860) spatial extent of piñon-juniper woodlands. We then couple historic spatial extent data with current aerial imagery and soil data in order to quantify how piñon-juniper extent has changed since 1860 across soil types. We hypothesize that the greatest rates of expansion will occur upon deeper, upland soil types that were historically dominated by a heavy herbaceous layer that likely historically supported a more frequent fire regime. In contrast, we hypothesize that piñon-juniper extent in the shallow, rocky soil types will be the same or even decline due to the limited effects of fire suppression and grazing on tree recruitment in these areas.

## **Materials and Methods**

*Study Area*

The study area is located in southeastern Colorado of the USA on predominantly privately managed land, specifically Chancellor and JE Canyon ranches, as well as some public military land (*Figure 1)*, which collectively cover approximately 400 square kilometers of semi-arid canyon-upland country. Elevations range from about 1370 meters in the bottom of the Purgatory River canyon, to up to 1700 meters in the upland areas. On average, the study area receives about 254 mm of precipitation a year, with nearly half of this precipitation falling during the summer monsoon months of July and August (National Weather Service). Temperatures at the study area range from an average January temperature of 0ºC to an average July temperature of 23 ºC.

The study area is comprised of a mosaic of upland and canyon topography, with one-seed juniper (*Juniperus monosperma*) dominating in the uplands, and piñon pine (*Pinus edulis*) co-dominant near the canyons and other areas of rocky, shallow soil. The Purgatory River Canyon and its accompaniment of steep side canyons drain the study area and contain ribbons of riparian species, as well as small, isolated pockets of ponderosa pine (*Pinus ponderosa*), Rocky Mountain juniper (*Juniperus scopularum*), and quaking aspen (*Populus tremuloides*) where springs and seeps emerge from the sandstone cliffs. Although the study area includes isolated patches of these other tree species, the two woodland species (one-seed juniper and piñon pine) are the most widespread and dominant and consequently tree cover changes are driven by changes in these woodland species.

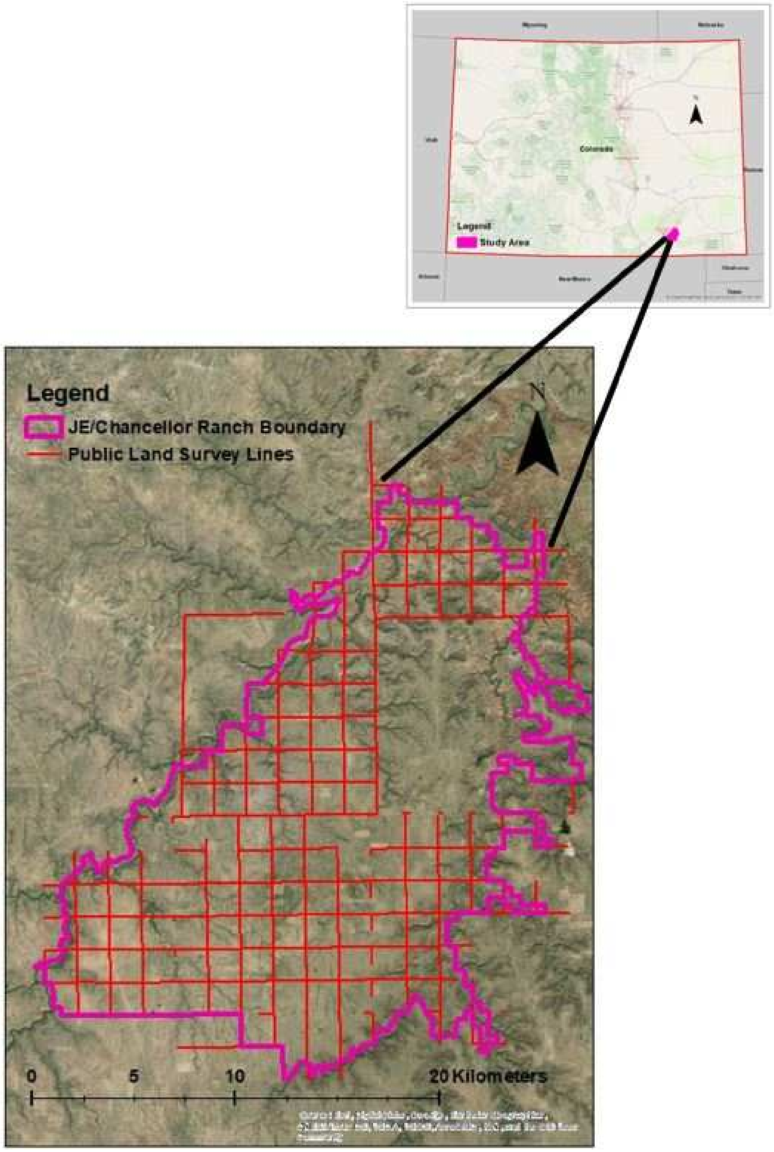



***Figure 1:*** *Area examined using General Land Office (GLO) observations and 2017 NAIP aerial imagery to assess changes in juniper cover in southeastern Colorado. Solid black lines denote 19th century GLO survey lines whereas the shaded pink area denotes JE Canyon and Chancellor Ranch.*

<u>*19th Century Woodland Cover*</u>

This study uses the U.S. General Land Office (GLO) surveys of southeastern Colorado to determine the spatial extent of piñon-juniper woodlands in our study area between the late 1860s and early 1880s (hereafter referred to as the 19th century). General Land Office (GLO) notebooks have been used extensively to determine the pre-settlement spatial structure of vegetation in various forested ecosystems (Bourdo, 1956; Bolliger et al., 2004; Galatowitsch, 1990; Manies & Mladenoff, 2000; Schulte & Mladenoff, 2001; Wang, 2005; Williams & Baker, 2011). The General Land Office was responsible for conducting the GLO as legislated by Congress in 1785. The Land Ordinance of 1785 called for the demarcation of US-held territory into 93.2 $km^2$ (36 square miles, 6 miles x 6 miles) townships. As surveyors set the boundaries of townships and the subdivisional (2.59 $km^2$ or 1 square mile blocks; 36 total) blocks within each township, they noted the vegetation and physical features of the land, as well as how they perceived the utility of a given township for agricultural or grazing purposes (Hoagland et al., 2017). GLO records represent a vast archive of data to look at large scale changes in vegetation where prior studies, photography, or other accounts are unavailable or infeasible (as is the case for dendrochronological studies in juniper-dominated ecosystems). The public land surveys have been used to reconstruct tree density Williams & Baker (2011), as well as forest distributions and even the spatial arrangement of single tree species on a landscape (Bourdo, 1956). GLO records are particularly advantageous for tree species such as *J. monosperma*, the dominant tree species in our study area, where accurate age-dating through dendrochronological methods is not possible due to the abundance of false and missing rings. These records are considered one of the most reliable and extensive sources for reconstructing past landscapes because of standardized data collection methods and systematic cover of most of the United States (Galatowitsch, 1990).

GLO records are available as photocopied files of the original, surveyor notebooks. Therefore, in the absence of search functions, each notebook must be manually perused for relevant data. In the present study, survey records were provided through The Official Public

Land Records Site as pdf files without any reference to location. Consequently, data collection for this project involved first scanning through all files for the appropriate township and range that contained the study area (*Figure 1*), and then translating all records into a geodatabase. This was made possible because surveyors would note the location (township, range, and section) and direction of movement when walking section lines and record observations of tree presence and abundance. Recording the distance along a section line at which an observation was made provided the exact location where surveyors entered and exited piñon-juniper woodlands on the field site in the late 19$^{th}$ century. Surveyors also noted whether or not half (800 meters) or whole (1600 meters) section lines contained piñon-juniper savanna which they would describe as scattered, isolated, or sparse timber (see *Table 1* below).

Although the patterns of movement and boundary-marking were systematically similar across surveyors, surveyors would often write their vegetation notes differently. As a result, we made certain interpretations of field notes in order to obtain useful data on 'timber' (piñon-juniper) cover across every section line (1.6 km [1 mile]). Below is a table (*Table 1*) that contains some qualitative vegetation notes of the surveyors and the corresponding tree density that we interpreted from these observations.

***Table 1:*** *Original surveyor observations and corresponding tree cover inferences. Note that, although the 2nd row says "timber poor," this information alone is not enough to claim that tree density was low, because sometimes surveyors would use "poor" to refer to timber quality.*

| **Surveyor Language** | **Tree Cover** |
|---|---|
| "Land rolling, soil 2nd rate" | Unknown |
| "Timber poor" | unknown |
| "Dense oak brush" | unknown |
| "Land rolling, prairie" | Open (no trees) |
| "Land rolling, bunchgrass" | Open (no trees) |
| "Dense piñon and cedar" | Woodland |
| "Dense cedar" | Woodland |
| "Timber poor, isolated cedar" | Savanna |
| "Timber poor, scattered cedars" | Savanna |

Surveyors would not always mention trees, or any form of vegetation at all, as shown in the first row of *Table 1*, and thus in these instances tree density would be recorded as unknown (NA). In other instances, surveyors would leave an ambiguous observation, such as "timber poor," in their field notebooks. If a surveyor wrote "timber poor," unaccompanied by any other information, it was unclear whether trees were present or not. Therefore, when a surveyor simply said, "timber poor," we recorded "NA" for timber density.

There were multiple cases where surveyors travelled through dense piñon-juniper stands, sometimes across the entire length of a 1.6 km section line or else noting the precise location at which they entered or exited these dense stands. In instances where the surveyor recorded they were crossing prairie and did not mention timber or any tree species, we assumed that at most there are only very isolated juniper trees in favorable spots or no trees at all. As such, these prairie areas were considered treeless (i.e. grassland) and tree density was assumed to be < 0.5 % (see *Analysis* section). We omitted line segments classified as savanna in the 19th century (n =

78) because surveyors would describe entire 1600 m section lines as having scattered trees, and we were unable to determine where across that entire section line trees were present.

The survey line data were converted to a shapefile (containing 1103 total line segments) to allow for geospatial analyses using ArcMap (version 10.4.1) and ultimately to assess changes in tree cover and associations with soil properties.

*Assessment of GLO Spatial Error*

Public land surveys were consistently conducted upon GLO gridlines, which are imported into modern mapping and spatial analysis tools in order to place where the surveyors walked, in addition to the locations of ecologically relevant observations along these gridlines. Errors in positioning by the surveyors sometimes slightly offset their true positions and directions of movement from modern GLO maps. As a result, studies focus on making *large-scale* inferences (stand scale and larger) of historic vegetation structure rather than small-scale analyses at the individual tree level (Wang, 2005; Williams & Baker, 2011). Here, we assessed the average spatial error of GLO records to then determine how sensitive our results are to the degree of spatial error in the data.

To assess the average spatial error of GLO records, we located areas on survey lines where surveyors identified distinct topographic landmarks that remain relatively stable overtime, such as the edges or bottoms of bluffs, cliffs, and mesas, in order to assess the spatial error of the surveyors. For example, if a surveyor noted that they reached the edge of a bluff at a specific location on a section line, that line was overlaid with current aerial imagery to estimate spatial error in the GLO records. Spatial error was obtained by determining the Euclidean distance between a surveyor's observed location and where a landmark truly existed according to the Bing aerial imagery base map (provided in ArcMap version 10.4.1). Spatial errors were calculated for each township (93.2 $km^2$) and average spatial error was computed using at least ten of these landmarks in a township (see *Table S4*). After magnitudes of error were established for each township, an overall average error was calculated for the entire study area, which was 13.9 m and subsequently used to assess the sensitivity of our results to spatial error (see analyses below).

*Remote Sensing Analyses*

We used National Agricultural Imagery Program (NAIP) aerial imagery from 2017 to quantify current tree cover within the study area. Using the aerial images, we drew approximately two hundred polygons with trees and two hundred without trees in ArcMap in order to train the computer to generate a raster map of 2017 tree cover at the field site. Two thousand random points were generated across the study site for validation and manually classified (using the original satellite imagery) as either 'Not Tree' (0) or 'Tree' (1) at the 1x1 meter pixel scale. The random points were then used to assess the accuracy of the classified raster map of tree cover by generating an error matrix where the random point values were compared to the cover map values. Measures of agreement and disagreement between the reference and created map were assessed using kappa statistics calculated from the error matrix, as well as quantity and allocation disagreement values, which point more specifically to the sources of error (disagreement) (Pontius & Millones, 2011; Salk et al., 2018; Warrens, 2015). Quantity and allocation disagreement values are generally considered substantial above values of 0.1 or 10% (Warrens, 2015). Kappa statistics between 0.2 and 0.4 generally denote fair agreement, followed by 0.4-0.6 as moderate agreement and anything exceeding 0.6 considered substantial agreement between the classified image and the actual data.

The final classified raster tree cover map had disagreement and kappa values of 0.2 and 0.5, respectively, indicating moderate agreement/accuracy at the 1 $m^2$ scale. Yet, because we were analyzing our data at much larger scales, we assessed the accuracy of our classified image at spatial scales relevant to our analyses. In order to compare changes in tree cover from the 19th century to present (more details below), we analyzed our data at the 30 m X 30 m scale, with trees binned into the following categories: <0.5% tree cover (open, i.e. no tree), ≥0.5% and <10% cover (savanna), and ≥10% tree cover (woodland). We randomly selected 20 different 30 m x 30 m sections around the study area in each classified cover category (for a total of 60 sections) and manually validated these classifications using the 2017 NAIP imagery. At this 30 m X 30 m (900 $m^2$) scale, the classified raster map had near perfect accuracy with the pixels binned into "open," "savanna," and "woodland" categories, with a total disagreement of 0.05 and kappa value of 0.925.

Although preexisting maps of tree cover are available, such as the LANDFIRE datasets from the United States Geological Survey, it was necessary to create a classified map of tree cover for our study area in order to achieve a high level of accuracy at the local scale. For example, while the LANDFIRE cover map of the study area agreed consistently with our classified cover map on areas of dense woodland near canyons, the LANDFIRE dataset did not identify the scattered trees in the upland areas that are mostly dominated by grassland. Therefore, since expansion into previously treeless areas was an important feature we wanted to document, the locally powerful classified cover map was extremely useful for its ability to show smaller, more scattered patches of trees.

*Tree Cover Change Analyses*

To assess changes in tree cover from the 19th century to 2017 over our study area, the 1103 19th century survey line segments were buffered by 15 meters on either side and the resulting buffer polygons were sectioned into 30 by 30 meter squares. These squares were overlaid with the 2017 classified map of tree cover and were used to assess changes in tree cover categories, with the 2017 squares classified as open (<0.5% tree cover), savanna (≥=0.5% and <10% cover), and woodland (≥10% cover). Thus, every square section on a survey line in which a vegetation observation was made was classified as having undergone either no changes in tree cover, expansion, or contraction (see *Table 2*). In total, 2051 900 $m^2$ polygons across the study area were used for our analyses to assess changes in tree cover from the 19th century to present.

***Table 2****: Possible tree cover changes between the 19th century and 2017. Tree cover was classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), or woodland (≥10% tree cover) in 2017.*

| | ***Open (2017)*** | ***Savanna (2017)*** | ***Woodland (2017)*** |
|---|---|---|---|
| ***Open (19th century)*** | No Change | Moderate Expansion | Expansion |
| ***Woodland (19th century)*** | Contraction | Moderate Contraction | No Change |

To test the hypothesis that juniper expansion is most likely to occur in areas of shallow soil depth with lower available water capacity, we used soil available water capacity data from the Soil Survey Geographic Database (SSURGO). SSURGO data is gathered using both aerial photography of tree coverage to infer soil type boundaries, as well as on the ground measurements. The SSURGO data gathered for our study area was compiled using a combination of both methods, and has been updated as recently as 2018. Tri-modal distribution (see *Figure S1*) of soil available water capacities (henceforth referred to as AWC) across the study area allowed for easy designation of soil AWC into the categories of "Low" (<10 cm), "Medium" (≥10cm and <20cm), and "High" (≥20cm). Line segments classified in terms of 150 year cover change were spatially joined with soil AWC data in order to assess how soil type affected the likelihood of tree cover change in a particular direction.

In order to assess whether changes in tree cover from the late 19$^{th}$ century to 2017 varied depending upon soil conditions, we performed a chi-square test of independence. We used an alpha criterion of 0.05 to test the null hypothesis that tree cover change varies completely independently of soil available water capacity. As such, a p-value ≤0.05 indicates that the amount of tree cover change varies depending upon the soil available water capacity.

<u>*Sensitivity Analyses*</u>

We assessed how sensitive our results were to: (1) the spatial error among the 19$^{th}$ century surveyors; and (2) the size of the buffer used along the survey line.

The average spatial error for the whole study area (13.9 m) was used to shift the survey lines by 13.9 meters in each cardinal direction (N, E, S, W). Thus, four new shapefiles were created, buffered by 15 meters, sectioned into 30 m X 30 m squares, and binned into the cover categories outlined above based on 2017 aerial imagery. Next, we analyzed tree cover change from the 19$^{th}$ century to 2017 using the four new shifted sets of 30 m X 30 m squares. We found our results were insensitive to the shifts in surveyor lines, with shifts in any cardinal direction resulting in similar (±3%) proportions of expansion and contraction (see *Tables S5-S8*).

GLO surveyors take notes to record vegetation characteristics along the survey line, yet it is unclear how far the surveyors would search beyond the transect line. As a result, we assessed how the results vary depending upon the size of the buffer used along the surveyor line to determine 2017 tree cover. In the analyses discussed above, we used a 15 meter buffer and thus conducted the analyses based on 30 m X 30 m squares. In order to test the effect of buffer size on the results, we conducted the same analysis with 5 meter and 10 meter buffers (e.g. 10 m X 10 m squares and 20 m X 20 m squares, respectively). These smaller buffers were used because surveyors were supposed to be recording vegetation along the survey line, and thus statements of exiting or entering a thicket of trees were likely based on nearby vegetation and thus smaller than the 15 meter buffer size used above.

## Results

Across our entire study area, we found evidence of significant woodland expansion and contraction. About 43% of all line segments categorized as open in the 19$^{th}$ century remained treeless, while about 39% of all 19$^{th}$ century woodlands remained woodlands in 2017 (see *Figure 2*). Overall, reductions in tree cover nearly equaled increases of tree cover on the landscape. Sixty one percent of 19$^{th}$ century woodland areas decreased below 10% tree cover, with 32% classified as savanna and 29% classified as open (treeless). Meanwhile, 57% of the areas that were described as open in the 19$^{th}$ century now have trees, with 23% classified as savanna and 34% classified as woodland.

The relative amounts of expansion compared to contraction are highly sensitive to the width of the buffers used along the survey lines. When the size of the buffer is reduced from 15 meters to 10 meters and finally to 5 meters, the reductions in tree cover increasingly outweigh expansions (see *Tables S1-S3*). For example, when using the smallest area of analysis (10 m X 10 m squares from the 5 meter buffer), we see only 45% of 19$^{th}$ century open areas that now have trees and 65% of 19$^{th}$ century woodland areas that have decreased below 10% tree cover. Thus, the 30 m X 30 m analysis (from the 15 meter buffer) is the most conservative in our estimates of contraction and may suggest greater expansion than actually occurred.

Although nearly equivalent amounts of tree cover expansion and contraction were observed in the study area overall, the locations of these changes strongly vary based on soil AWC ($\chi^2$ (10, N = 1945) = 700.59, $P < 0.001$; see *Figure 3*). Most expansion occurred in areas of low soil AWC, with 29% of all 19$^{th}$ century open areas in low soil AWC becoming savanna and 59% of these areas becoming woodland by 2017. Areas with medium and high soil AWC saw much less expansion and instead experienced significant reductions in tree cover. Respectively, 38% and 46% of woodlands became open in areas of medium and high soil water capacity, while areas with low soil AWC only saw 13% of $19^{th}$ century woodlands become open. Notably, all open areas that became woodland by 2017 occurred in areas of low soil AWC. As a result, we found an almost complete relegation of expansion to areas with low soil AWC, while the areas that show the most extensive woodland contraction are confined to soils with higher soil AWC (see *Figures 3, 4*).

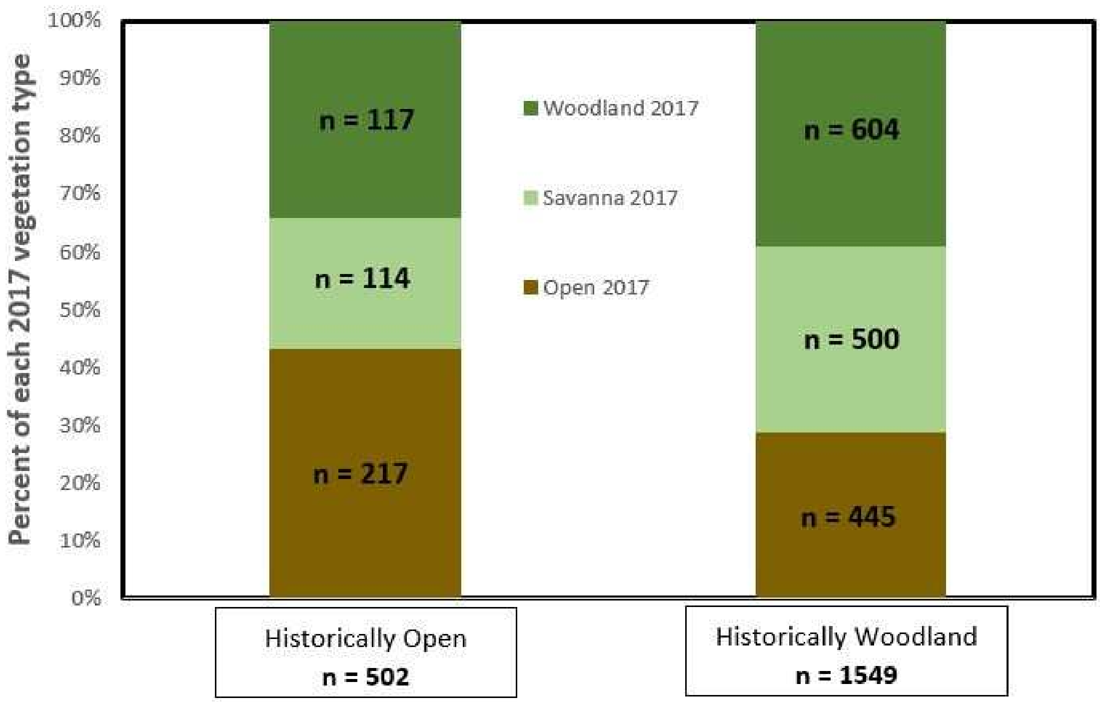
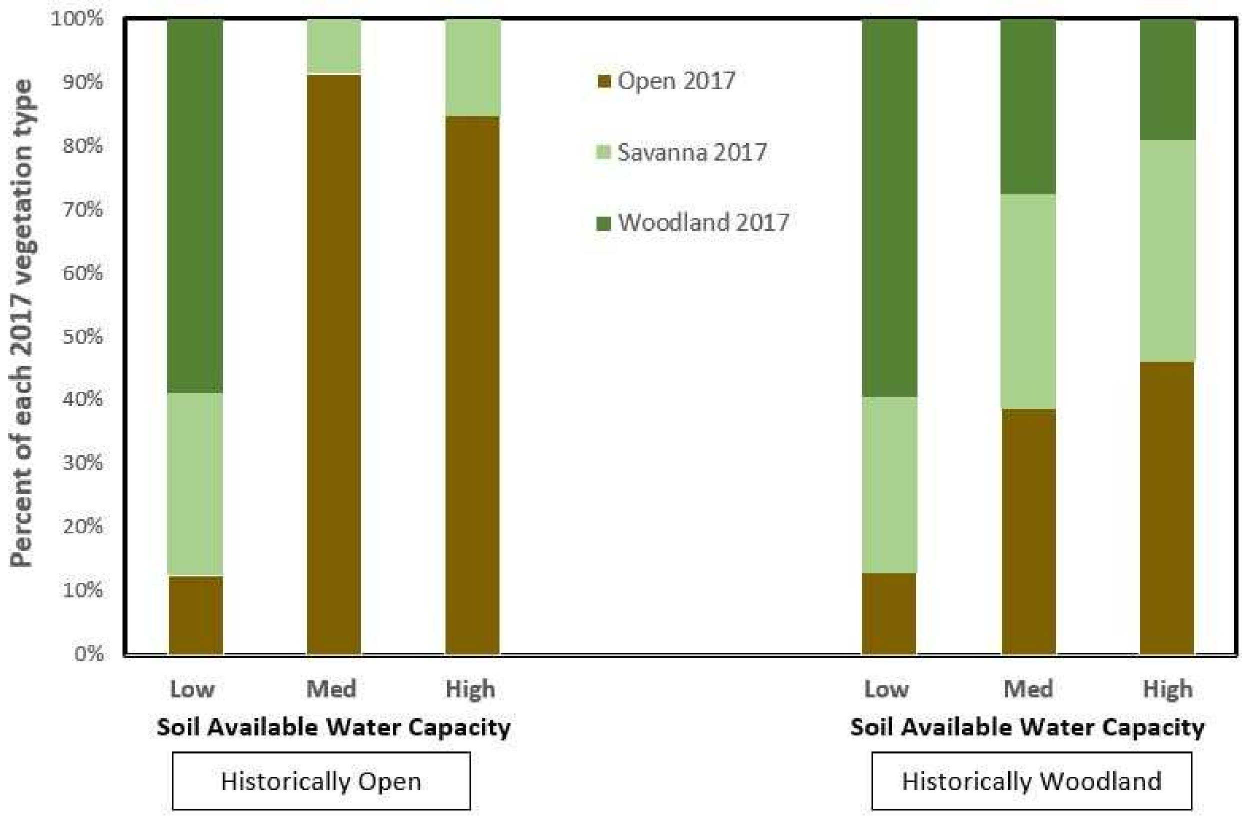



***Figure 2:*** *Percent of $19^{th}$ century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017. These tree cover changes were analyzed by buffering the survey lines by 15 meters and sectioning these buffers into 30 m X 30 m squares of analysis.*

***Table 3***: *Percent of 19th century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017 as a function of soil available water capacity (AWC) in centimeters. Soil AWC categories consist of "Low AWC" (<10 cm), "Medium AWC" (>= 10cm and <20cm) and "High AWC" (>=20cm). Tree cover changes were analyzed by buffering the survey lines by 15 meters and sectioning these buffers into 30 m X 30 m squares of analysis.*

| | 19th Century Cover | Open (2017) | Savanna (2017) | Woodland (2017) | Totals |
|---|---|---|---|---|---|
| Low AWC | No | 37 (12.50%) | 85 (28.72%) | 174 (58.78%) | 296 (100%) |
| | High | 101 (12.87%) | 219 (27.90%) | 465 (59.23%) | 785 (100%) |
| Medium AWC | No | 74 (91.36%) | 7 (8.64%) | 0 (0%) | 81 (100%) |
| | High | 43 (38.39%) | 38 (33.93%) | 31 (27.68%) | 112 (100%) |
| High AWC | No | 106 (84.80%) | 19 (15.20%) | 0 (0%) | 125 (100%) |
| | High | 301 (46.17%) | 226 (34.66%) | 125 (19.17%) | 652 (100%) |

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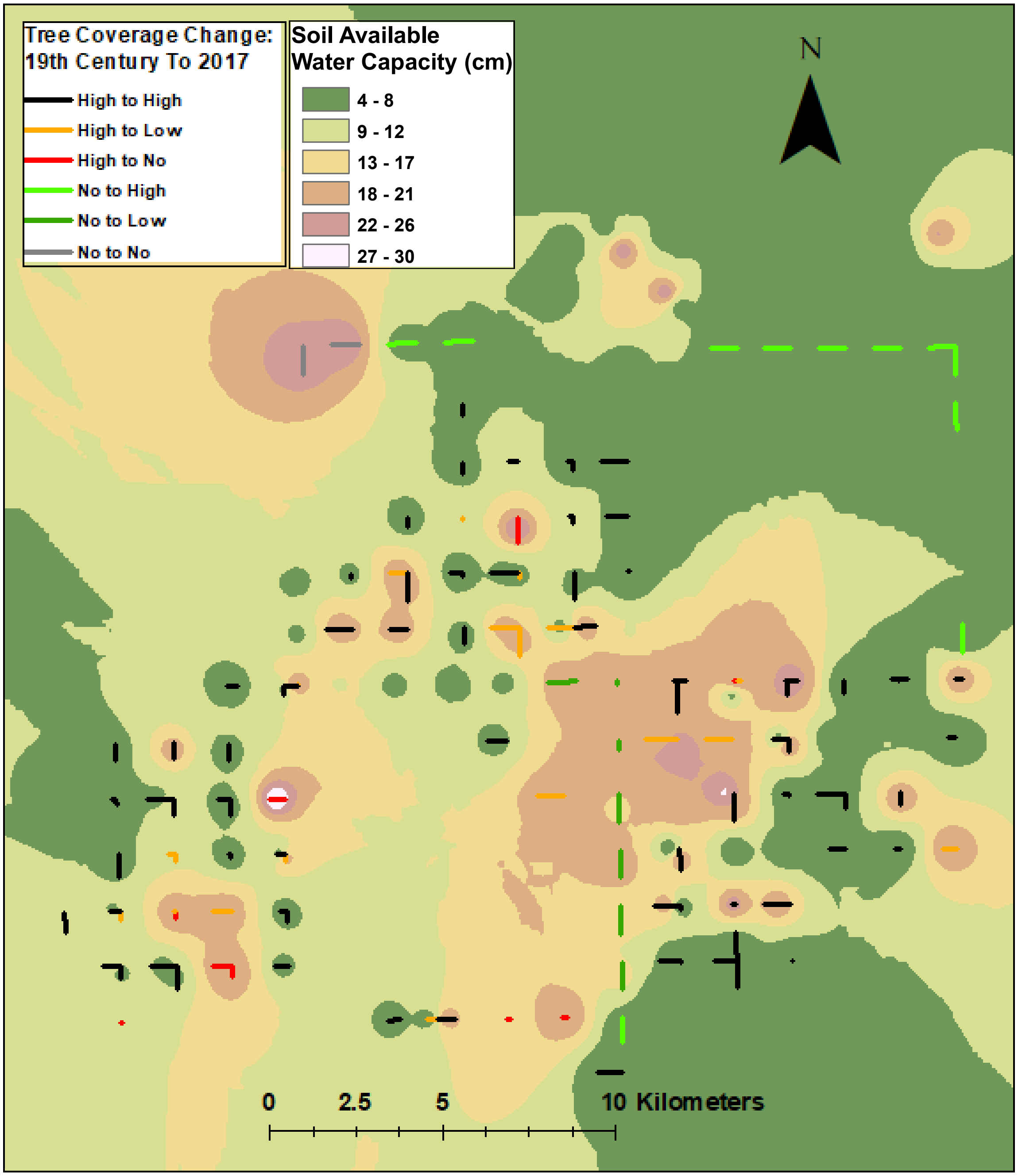


***Figure 4:*** *Change in tree cover in the study area from the 19th century until 2017, overlaid upon soil available water capacity (cm of depth). Woodlands have persisted almost exclusively in areas of low soil available water capacity (black lines) whereas areas with higher soil available water capacity have declined in cover and extent (orange and red lines, respectively). Woodlands expanded into historically open areas (bright green lines) in locations of low soil available water capacity.*

## Discussion

Piñon-juniper expansion in the semi-arid ecosystems of western North America has been well documented in the scientific literature from the early 1900s onwards (Johnsen, 1962; Belsky, 1996; Miller & Rose; 1999; Miller et al., 2008; Romme et al., 2009). This expansion of piñon-juniper woodlands is often attributed to more unnatural drivers such as fire suppression and grazing, which has led to widespread tree removal treatments across the U.S. Southwest (Redmond et al., 2014; Romme et al., 2003). Over the last 150 years in our study area in southeastern Colorado, we documented evidence of both expansion and contraction with a slightly greater portion of the study area having declined in tree cover, counter to the general assumption that these woodlands have expanded in most areas. Importantly, changes in woodland cover were strongly associated with soil properties. Specifically, woodland contraction generally occurred in areas of high soil AWC whereas woodland expansion generally occurred in areas of low soil AWC. These results suggest that ongoing management efforts in this region to reduce tree density in settled, upland areas with higher soil AWC are driving these historically woodland areas to become unnaturally open grasslands rather than restoring their historic structure and function.

*Woodland Contraction*

Our results show significant contractions of piñon-juniper woodlands occurring almost exclusively in areas of medium and high soil AWC. The areas of higher soil AWC are most commonly located in the uplands with deeper, fine-grained soil where grasses tend to be more dominant (Gascho Landis & Bailey, 2005; Romme et al., 2003; Miller et al., 2008). Moreover, the properties of the upland soils were much more amenable to settlement when compared with the rocky canyon rims, and therefore increased woodcutting pressures likely occurred across the uplands in our study area.

***Figure 5:*** *An abandoned homestead (left) and corral (right) at the center of an upland area that was historically dense woodland and has since reduced in tree cover*

In 1862, the Homestead Act was signed into law, allowing for homesteaders to purchase government land if they could reasonably demonstrate they had improved (cultivated) the land after 5 years (Finkelman & Garrison, 2014). An account from a long time local rancher and Nature Conservancy property manager estimates as much as 80 abandoned homesteads exist within the study area (JJ Autry, *personal communication*). Indeed, in visiting one of the upland areas that was recorded as dense woodland in the past yet treeless today, we found traces of cleared fields gone fallow, as well as large amounts of timber cut for fencing, living structures, and corrals (see *Figure 5*). Despite a general local feeling that upland areas have expanded in tree cover, historical accounts by local ranchers in the region as well as physical evidence on the landscape (e.g. prevalence of axe cuts) corroborates pervasive past woodcutting. Tree loss was greatest in upland areas of deep, high AWC soil that supports greater grass production, which is where we hypothesize that most people chose to settle, attempt to farm, and manage the land for ranching.

*Woodland Expansion*

Our data suggest that fire suppression and grazing, the two commonly cited reasons for expansion and consequent modern tree removal, were likely not the primary drivers of woodland expansion. Most expansion of piñon-juniper woodlands was relegated to rocky, shallow areas of low soil AWC that have little herbaceous cover. The low amounts of herbaceous cover limit the spread of fire in these areas, resulting in long fire return intervals and thus encourages the establishment and persistence of trees (Floyd et al., 2004; Huffman et al., 2008; Shinneman & Baker, 2009). Moreover, although cattle grazing can reduce herbaceous cover and thereby increase resources for tree establishment (Johnsen, 1962; Bachelet et al., 2000; Gascho Landis & Bailey, 2005) we know from local accounts (JJ Autry; Chris Pague, *personal communication*) that cattle are rotated every 5 years between upland pastures (e.g. high soil AWC, greater grass production) and that the rough, rocky, woodland areas of low soil AWC near canyon rims are generally avoided. These rugged soil types near steep slopes and bluffs would have also likely been considered inhospitable by settlers in the late 19th century, especially in terms of attempting to cultivate the land and raise cattle. Consequently, expansion of woodlands over the last 150 years in our study area in areas of low soil AWC is unlikely due to fire suppression or grazing.

While long fire return intervals and lack of woodcutting in areas of low soil AWC likely explain why woodlands persisted, the establishment and expansion of woodlands in these areas are more likely due to climatic factors. Most likely, historic periods of cool and wet climatic conditions over the last 150 years at our study area promoted tree establishment as seen in other areas of the U.S. Southwest (Barger et al., 2009; Shinneman & Baker, 2009).

*Limitations*

The biggest limitation of this study is the available information on historic woodland structure from GLO data. In addition to relying on qualitative accounts of woodland structure rather than quantitative estimates of percent tree cover, we also lack data on the distance away from a survey line that was used to make tree cover observations. Consequently, in our interpretation of the results, we focus mainly on changes from historically woodland to open and from historically open to savanna/woodland. Due to the uncertainty in the field of view used by surveyors to qualitatively estimate woodland structure, we tested three different fields of view by buffering survey lines by 5, 10, and 15 meters. When analyzing the results with narrower buffers, we found woodland contractions to increasingly outweigh expansions (see *Tables S1-S3*). These smaller buffer widths (e.g. narrower fields of view) may be more realistic given that surveyors were tasked with quantifying what they encountered on the lines that they walked. However, we focus on the results from the 15 meter buffer (30 m X 30 m sections) scale of analysis in order to be conservative in our estimates of contraction, given that the current paradigm is that woodlands have generally expanded. Importantly, regardless of the scale of analysis, it is clear that the story of vegetation change on this landscape is not merely one of tree expansion, and that the locations of both contraction and expansion in relation to soil AWC values are consistent with the land use history of our study area.

Another important limitation of this study is that GLO surveyors' notes would not always provide information on vegetation structure. As a result, only 25% of the total distance of surveyed lines were used in these analyses. We hypothesize that the GLO surveyors were more likely to report occurrences of trees than absences of trees, and this may explain why the majority of areas with historic vegetation information were described as savanna or woodland rather than open (treeless). Due to this constraint, we identified the proportion of areas that were historically open but experienced expansion and the proportion of areas that were historically woodland but experienced contraction, rather than comparing which percentage of the landscape was historically open in the past relative to today.

Finally, research was conducted on privately managed cattle ranches in southeastern Colorado rather than public land and thus the results of this study are only applicable to our study area, although similar dynamics may occur elsewhere. Notably, previous documentations of piñon-juniper cutting during the incipient stages of Euro-American settlement (Bahre & Hutchinson, 1985; Evans, 1988; Ko et al., 2011) and more recent piñon-juniper cutting (Redmond et al., 2014) also occurs on public land commonly grazed by cattle, particularly Bureau of Land Management land. Thus, the trends documented here that appear to be driven by early settlement cutting likely also occurred in piñon-juniper woodlands elsewhere.

## Conclusions and Management Implications

The findings of this paper do not support the widespread assumption that there has been a general expansion and thickening in piñon and juniper woodlands due to the unnatural effects of fire suppression and grazing since Euro-American settlement. We expected upland settlement and subsequent grazing and fire suppression of these lands to lead to substantial amounts of woodland expansion in the deeper upland soil types over the last 150 years. On the other hand, we hypothesized that the less settled, rocky, inhospitable areas of shallow soil near the canyon rims would remain relatively consistent in tree cover over time. Instead, we found substantial woodland contraction over the last 150 years across the settled, upland areas with higher soil AWC. Across the study area, tree increases nearly balance out reductions, however we found that most increases were spatially relegated to rocky, shallow soils of low AWC near canyon rims, where piñon-juniper woodlands are most commonly documented.

From these results, we recommend discontinuing piñon and juniper removal treatments in upland areas of high soil AWC if the goal of these treatments is to return to the historical range of tree cover variability at just prior to Euro-American settlement (mid-19$^{th}$ century). Active tree-reduction treatments are ongoing in southeastern Colorado and other regions, often under the assumption that these woodlands are unnaturally dense. These results suggest caution in implementing treatments to restore ecosystem structure if changes in woodland extent from the very onset of settlement have not been assessed. This is critical as unnecessary piñon and juniper removal is likely to be detrimental to local wildlife species richness and diversity, as woodlands provide important habitat for many animals (Bombaci & Pejchar (2016); Gallo et al

(2016)), and especially given recent and projected increases in widespread drought-induced piñon mortality over the past several decades (Breshears et al (2005); Shaw et al (2018); Hartmann et al (2018)) and recruitment failure (Redmond et al., 2012; Redmond et al., 2015). Interestingly, dense thickets of trees near canyon rims limit the bighorn sheep's ability to escape quickly from predators between their canyon water sources and upland grazing areas (Smith et al., 1991). Our results indicate that tree removal treatments in rocky areas with low soil available water capacity is potentially more ecologically viable given these areas have experienced increases in tree cover since the $19^{th}$ century. However, these increases were most likely due to periodic cool and wet episodes of climate over the last 150 years, rather than fire suppression and grazing. This suggests that these woodlands are not unnaturally dense and that continued persistence of woodlands near the canyon rims may closely depend on future climate. The usage of GLO data to assess changes in woodland cover since Euro-American settlement provides useful insights and can help aid management of these semi-arid ecosystems across the western US.

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**Supplementary Materials:**

*Line of Sight Sensitivity Analysis*

***Table S1***: *Percent of 19th century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017. These tree cover changes were analyzed by buffering the survey lines by 5 meters and sectioning these buffers into 10 m X 10 m squares of analysis.*

| | Open (2017) | Savanna (2017) | Woodland (2017) | Totals |
|---|---|---|---|---|
| Open (19th century) | 816 (55.36%) | 200 (13.57%) | 458 (31.07%) | 1474 (100%) |
| High trees (19th century) | 2038 (45.94%) | 866 (19.52%) | 1532 (34.54%) | 4436 (100%) |

***Table S2***: *Percent of 19th century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017. These tree cover changes were analyzed by buffering the survey lines by 10 meters and sectioning these buffers into 20 m X 20 m squares of analysis.*

| | Open (2017) | Savanna (2017) | Woodland (2017) | Totals |
|---|---|---|---|---|
| Open (19th century) | 354 (47.26%) | 144 (19.23%) | 251 (33.51%) | 749 (100%) |
| High trees (19th century) | 779 (34.33%) | 640 (28.21%) | 850 (37.46%) | 2269 (100%) |

***Table S3***: *Percent of 19th century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017. These tree cover changes were analyzed by buffering the survey lines by 15 meters and sectioning these buffers into 30 m X 30 m squares of analysis.*

| | ***Open (2017)*** | ***Savanna (2017)*** | ***Woodland (2017)*** | ***Totals*** |
|---|---|---|---|---|
| ***Open (19th century)*** | 217 (43.23%) | 114 (22.71%) | 171 (34.06%) | 502 (100%) |
| ***High trees (19th century)*** | 445 (28.73%) | 500 (32.28%) | 604 (38.99%) | 1549 (100%) |

*Surveyor Spatial Error Sensitivity Analysis*

***Table S4***: *Average surveyor spatial error (in meters) by township/range in the study area.*

| Township/ Range | *30/56* | *30/57* | *31/56* | *31/57* | *31/58* | *32/57* | **Study Area Average:** |
|---|---|---|---|---|---|---|---|
| Avg. Spatial Error (m) | 11.72 | 11.71 | 19.34 | 11.26 | 17.49 | 9.74 | **13.9** |

***Table S5***: *Percent of 19th century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017. These tree cover changes were analyzed by* ***shifting all survey lines 13.9 meters to the north****, buffering by 15 meters, and sectioning these buffers into 30 m X 30 m squares of analysis.*

| | ***Open (2017)*** | ***Savanna (2017)*** | ***Woodland (2017)*** | ***Totals*** |
|---|---|---|---|---|
| ***Open (19th century)*** | 215 (42.91%) | 117 (23.35%) | 169 (33.74%) | 501 (100%) |
| ***High trees (19th century)*** | 434 (27.93%) | 497 (31.98%) | 623 (40.09%) | 1554 (100%) |

***Table S6***: *Percent of 19th century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017. These tree cover changes were analyzed by* ***shifting all survey lines 13.9 meters to the east****, buffering by 15 meters, and sectioning these buffers into 30 m X 30 m squares of analysis.*

| | ***Open (2017)*** | ***Savanna (2017)*** | ***Woodland (2017)*** | ***Totals*** |
|---|---|---|---|---|
| ***Open (19th century)*** | 227 (44.69%) | 103 (20.28%) | 178 (35.03%) | 508 (100%) |
| ***High trees (19th century)*** | 451 (29.30%) | 472 (30.67%) | 616 (40.03%) | 1539 (100%) |

***Table S7***: *Percent of 19th century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017. These tree cover changes were analyzed by* ***shifting all survey lines 13.9 meters to the south****, buffering by 15 meters, and sectioning these buffers into 30 m X 30 m squares of analysis.*

| | ***Open (2017)*** | ***Savanna (2017)*** | ***Woodland (2017)*** | ***Totals*** |
|---|---|---|---|---|
| ***Open (19th century)*** | 213 (42.26%) | 118 (23.41%) | 173 (34.33%) | 504 (100%) |
| ***High trees (19th century)*** | 459 (29.73%) | 479 (31.02%) | 606 (39.25%) | 1544 (100%) |

***Table S8***: *Percent of 19th century open (treeless) and woodland areas that were classified as open (<0.5% tree cover), savanna (≥0.5% and <10% tree cover), and woodland (≥10% tree cover) by 2017. These tree cover changes were analyzed by* ***shifting all survey lines 13.9 meters to the west****, buffering by 15 meters, and sectioning these buffers into 30 m X 30 m squares of analysis.*

| | ***Open (2017)*** | ***Savanna (2017)*** | ***Woodland (2017)*** | ***Totals*** |
|---|---|---|---|---|
| ***Open (19th century)*** | 222 (44.22%) | 105 (20.92%) | 175 (34.86%) | 502 (100%) |
| ***High trees (19th century)*** | 452 (29.35%) | 471 (30.58%) | 617 (40.07%) | 1540 (100%) |

*Histogram Data*

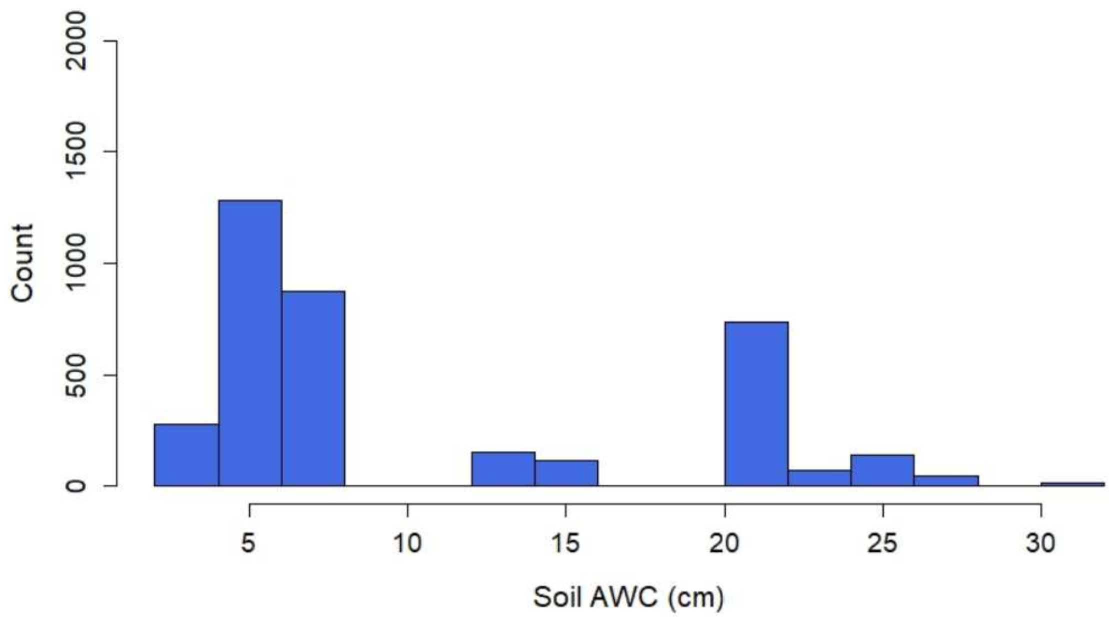


***Figure S1:*** *Count (number) of historically open and woodland 30 m X 30 m analysis squares that display different levels of soil available water capacity (AWC) in centimeters. Note the tri-modal distribution that was split into "Low AWC" (<10 cm), "Medium AWC" (≥10cm and <20cm) and "High AWC" (≥20cm) for analysis.*

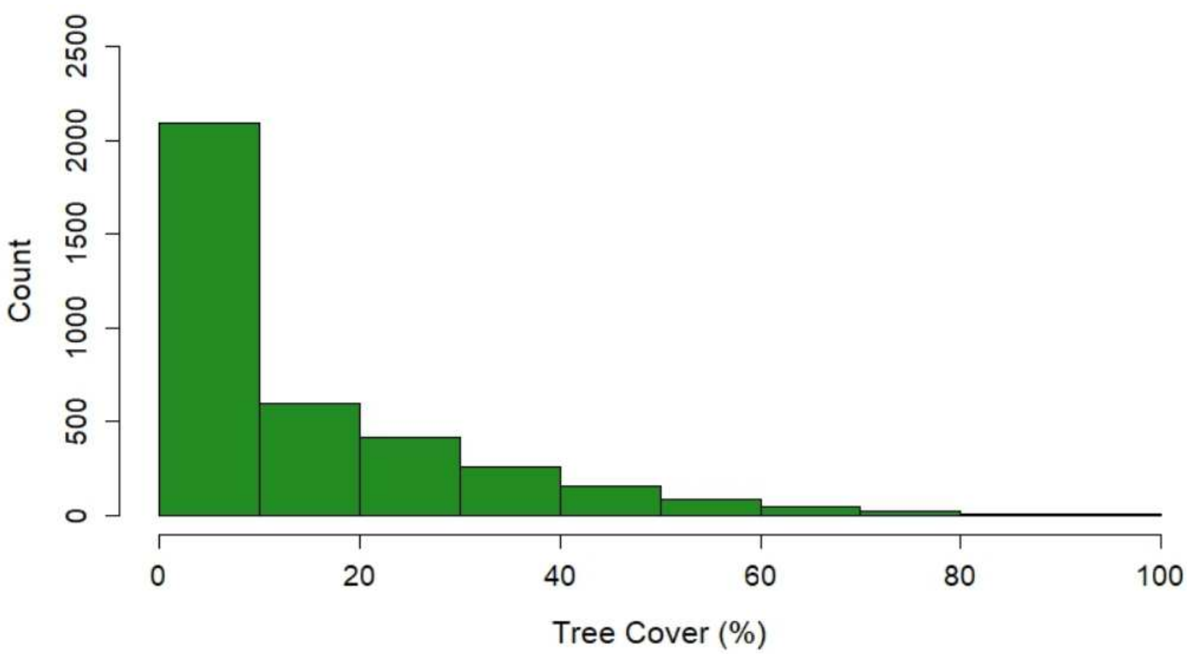


***Figure S2:*** *Count (number) of historically open and woodland 30 m X 30 m analysis squares that display different amounts of percent tree cover in 2017.*