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Authors: Amme, Noah, Pague, Chris A., and Redmond, Miranda D.

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Change in Piñon-Juniper Woodland Cover Since Euro-American Settlement: Expansion Versus Contraction Associated with Soil Properties ☆

Noah Amme[a], Chris A. Pague[b], Miranda D. Redmond[a,*]

[a] Department of Forest and Rangeland Stewardship, Colorado State University, Fort Collins, CO, 80523, USA
[b] The Nature Conservancy, Boulder, CO, 80302, USA

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ABSTRACT

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 western United States. 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 half a century after Euro-American settlement. Yet US General Land Office (GLO) surveys provide valuable insight into the historical extent and density of woodland and forest ecosystems as surveyors would note where on the landscape they entered and exited woodlands or forests and provided qualitative estimates of relative tree density. This study uses these 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 these data with 2017 aerial imagery of woodland cover. We found substantial amounts of woodland contraction, as well as expansion: ≈61% of historically dense woodland is now savanna or open (treeless), whereas ≈57% of historically open areas are now savannas or woodlands. The highest rates of expansion occurred on shallow, rocky soil types with low soil available water capacity, which support little herbaceous vegetation and were consequently less likely to be affected by fire suppression or grazing. Meanwhile, the significant contractions in woodland extent occurred on deeper, upland soils with higher soil available water capacity, which were likely where early settlement and tree cutting was most prevalent. Our results provide mixed support for the widespread assumption of woodland expansion since Euro-American settlement in southeast Colorado and suggest that the expansion that has occurred in our study area is unlikely a result of past grazing or fire suppression.

Introduction

Woodland and forest ecosystems across western North America have experienced increased density and expansion since the early 1900s due to a suite of factors that signify both anthropogenic and nonanthropogenic change. Nonanthropogenic factors (i.e., factors unrelated to humans) include increased tree recruitment during climatically favorable (cool and wet) periods (Barger et al. 2009; Shinneman and Baker 2009), recovery following natural disturbances that occurred in the 19th century (e.g., wildfire, insect infestations; Romme et al. 2009), and an overall expansion of many tree species ranges across the West due to the steady, ongoing climatic emergence from the last Ice Age (Hewitt 1996; Clark 1998; Johansen and Latta 2003). Since Euro-American settlement, dramatic changes in land use have initiated more anthropogenic pressures on tree species ranges through grazing, fire exclusion, and woodcutting (Bahre and Hutchinson 1985; Evans 1988; Bachelet et al. 2000; Ko et al. 2011). This expansion due to anthropogenic and nonanthropogenic factors has been documented to occur in many areas dominated by piñon pine *(Pinus edulis; P. monophyla)* and juniper *(Juniperus osteosperma; J. monosperma)* ecosystems, a widespread vegetation type in the US Southwest (Johnsen 1962; Jacobs et al. 2008; Romme et al. 2009).

The majority of scientific literature documents piñon-juniper expansion using initial stand structure data from the early 1900s onwards (Johnsen 1962; Miller and Rose 1995; Belsky 1996; Romme et al. 2009), often concluding that these woodlands are currently unnaturally dense and widespread. However,

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* Correspondence: Dept of Forest and Rangeland Stewardship, 1001 Van Dyken Way, Fort Collins, CO 80523, USA.
E-mail address: Miranda.Redmond@colostate.edu (M.D. Redmond).

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Euro-American influence on these ecosystems has existed since settlement and natural resource exploitation began in the US Southwest in the mid to late 19th century (Evans 1988), so observed expansion since the 1900s could be recovery from earlier woodcutting. Across the semiarid US 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, 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 and Hutchinson 1985; Ko et al. 2011). Since much of the expansion literature dates only to the early 20th century, it is critical 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 19th century (1869–1881) 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 in a piñon-juniper woodland.

Initial logging and woodcutting in the mid to late 1800s in piñon-juniper ecosystems may have reduced woodland density and extent, whereas fire suppression and grazing beginning in the 20th century may have contributed to the densification and expansion of piñon-juniper ecosystems. Piñon-juniper woodlands are often characterized by an infrequent, high-severity fire regime (> 250-yr recurrence), such that fire exclusion in these woodland types does not significantly influence tree cover (Floyd et al. 2004; Huffman et al. 2008; Shinneman and Baker 2009). However, piñon-juniper ecosystems dominated by a heavy grass component that are more savanna-like can carry surface fire much easier, resulting in more frequent, low-severity fires on a decadal time scale (Romme et al. 2009; Margolis 2014). Consequently, fire exclusion in these savanna-like landscapes would likely result in an increase in tree seedling density (Margolis 2014). Human land use change may have also increased tree establishment through grazing of domestic ungulates. Piñon-juniper ecosystems exist in semiarid environments, and interspecific competition for water between tree seedlings and herbaceous understory plants has been hypothesized to limit tree establishment (Chambers et al. 1999; Redmond et al. 2015). 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 and 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 that historically carried surface fires.

The effects of fire exclusion and grazing in piñon-juniper woodlands vary due to the soil type and associated 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 ecosystems tend to be dominated by deep, fine-textured soils such as in eastern New Mexico (Margolis 2014), whereas woodland environments are often relegated to shallow, rocky, or coarse-textured soils (Romme et al. 2003; Gascho Landis and Bailey 2005). Since soil type has a large influence on herbaceous vegetation, it can be a robust predictor of the historic fire regime. 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 as they likely would have supported livestock grazing and historically carried frequent surface fire before the introduction of fire suppression.

The documented expansion of piñon-juniper woodlands is often attributed to the more anthropogenic drivers of fire suppression and grazing, leading to widespread treatments across the western United States (Romme et al. 2003; Redmond et al. 2013, 2014). However, there are also reasons why piñon-juniper woodlands may have expanded since the early 1900s that are unrelated to human activity, such as a response to cool and wet climate pulses (Barger et al. 2009; Shinneman and Baker 2009) or recovery from past disturbances (Romme et al. 2009). In addition, these woodlands may be simply recovering from past woodcutting (Bahre and Hutchinson 1985; Evans 1988; Ko et al. 2011). Further, more recent woodland contraction may be occurring due to not only widespread tree-removal treatments (Romme et al. 2003; Redmond et al. 2013, 2014) but also hotter droughts that have led to extensive tree mortality and subsequent recruitment failure in many piñon-juniper ecosystems across the region (Breshears et al. 2005; Redmond et al. 2015, 2018). 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 and assess whether changes occurred in areas expected to be most strongly influenced by fire suppression and grazing.

This paper assesses the degree of expansion and contraction of piñon-juniper woodlands since the late 19th century and how that varies depending upon soil type. Using the first General Land Office (GLO) surveys of southeastern Colorado from the late 19th century, we first determine the historic (1869–1881) 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 the late 19th century across soil types. We hypothesize that the greatest rates of expansion will occur on 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 contract 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 United States on predominantly privately managed land, specifically Chancellor and JE Canyon ranches. Approximately 2% of the study area lies within the modern-day Piñon Canyon Maneuver Site, with an additional 1% of all transects falling in the Comanche National Grassland. The study area collectively covers ≈400 km^2 of semiarid canyon-upland country (Fig. 1). Elevations range from about 1 370 m in the bottom of the Purgatoire River canyon to up to 1 700 m in the upland areas. On average, the study area receives about 254 mm of precipitation a yr, with nearly half of this precipitation falling during the summer monsoon months of July and August (PRISM Climate Group 2018). Average monthly temperatures range from 0°C in January to 23°C in July.

The study area comprises a mosaic of upland and canyon topography, with one-seed juniper (*Juniperus monosperma* Engelm.) dominating in the uplands and piñon pine (*Pinus edulis* Engelm.) codominant near the canyons and other areas of rocky, shallow soil. The Purgatoire 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* Engelm.), Rocky Mountain juniper (*Juniperus scopularum* Sarg.), and quaking aspen (*Populus tremuloides* Michx.), where springs and seeps emerge from the north-facing sandstone cliffs. Although the study area includes isolated patches of these other tree species, the two woodland species (one-seed juniper and

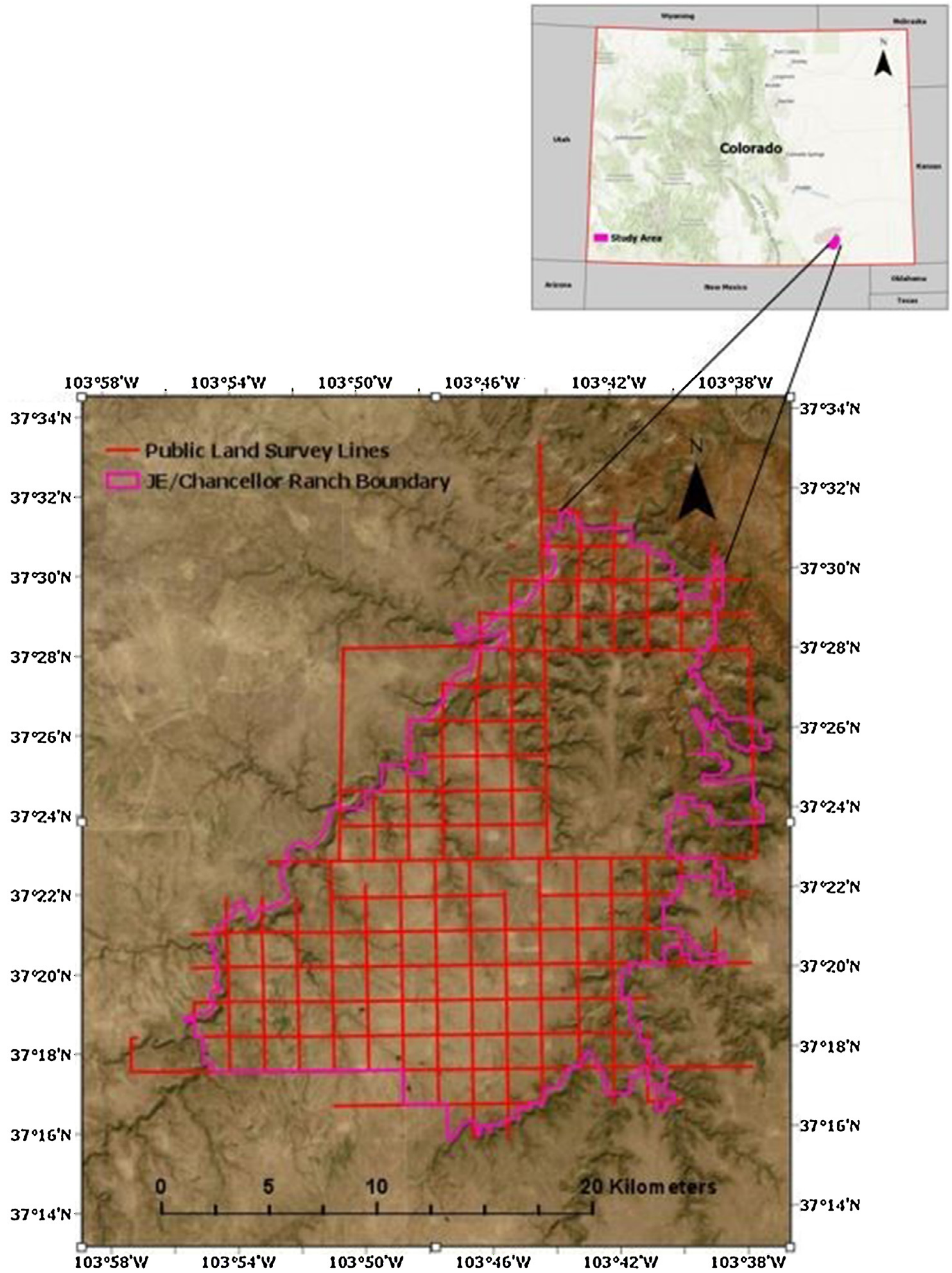

Fig. 1. Area examined using General Land Office (GLO) observations and 2017 NAIP aerial imagery to assess changes in juniper cover in southeastern Colorado. *Solid black lines* denote 19th century GLO survey lines, whereas the *shaded pink area* denotes JE Canyon and Chancellor Ranch.

piñon pine) are the most widespread and dominant and consequently documented tree cover changes are driven by changes in these woodland species.

Large-scale grazing in the study area began in 1869 with the formation of JJ Ranch, later acquired by the Prairie Cattle Company in 1882. However, large numbers of homesteaders did not settle in the study area until the early 20th century, eventually totaling 100 or more properties (Keck 1999). Grazing during this early period took the form of open-range grazing (Stone 1918). Market changes and severe blizzards led to the liquidation of the Prairie Cattle Company in 1916, and subsequent falling cattle prices combined with the Dust Bowl and the Great Depression forced most landowners to sell or abandon their properties (Egan 2006). The 1940s, especially during World War II, brought lucrative prices for beef and resulted in the assembly of larger private ranches by mostly local families that generally used continuous grazing practices, which continued into the 1990s. These spatially extensive ranches are still grazed today, although managed for a variety of purposes including wildlife habitat. Piñon and juniper trees have been periodically removed or thinned in places as finances allow to increase forage production for livestock, promote certain wildlife species, and in an effort to restore these ecosystems to their historical structure due to the prevailing assumption of woodland expansion and thickening since Euro-American settlement.

19th century woodland cover

This study uses the US GLO surveys of southeastern Colorado to determine the spatial extent of piñon-juniper woodlands in our study area between the 1869 and 1881 (referred to as the

Table 1
Original surveyor observations and corresponding tree cover inferences used in analyses. Surveyors referred to juniper as "cedar." Savannas were omitted from analyses as these were used to describe entire section lines (1.6 km), and as a result it was unclear where along those lines trees were located.

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
"Thicket of cedar"	Woodland
"Timber poor, isolated cedar"	Savanna
"Timber poor, scattered cedars"	Savanna

19th century). GLO notebooks have been used extensively to determine the presettlement spatial structure of vegetation in various forested ecosystems of the United States (Bourdo 1956; Galatowitsch 1990; Manies and Mladenoff 2000; Bolliger et al. 2004; Schulte and Mladenoff 2001; Wang 2005; Williams and Baker 2011). The GLO was responsible for conducting its work as legislated by the US 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 × 6 miles) townships. As surveyors set the boundaries of townships and 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 and 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 (see Fig. 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 location where surveyors entered and exited piñon-juniper woodlands on the field site in the late 19th century. Surveyors also noted whether entire section lines (1 600 m) contained piñon-juniper savanna, which they would describe as scattered, isolated, or sparse timber (Table 1). Surveyors did not mention the presence of tree stumps, which would have indicated additional historical tree cover. This suggests that very few trees had been cut before these historic surveys as they occurred during the earliest stages of Euro-American settlement.

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 classified surveyors' qualitative notes on tree cover into corresponding tree density groupings (open, savanna, or woodland; see Table 1). Surveyors would not always mention trees, or any form of vegetation, and thus in these instances tree density was unknown (i.e., NA in Table 1) and omitted from subsequent analyses. If a surveyor wrote "timber poor," unaccompanied by any other information, it was unclear whether trees were present or not. Line segments classified as savanna in the 19th century ($n = 78$) were also omitted from analyses because surveyors would describe entire 1 600-m section lines as having scattered trees and it was unknown where across that entire section line trees were present. Survey line data were converted to a shapefile 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 and 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 over time, 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 he or she 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) by using at least 10 of these landmarks, with the spatial error ranging from 9.7 m to 19.3 m across the townships (Table S1; available online at …). The overall average spatial error of our study area was 13.9 m and was subsequently used to assess the sensitivity of our results to spatial error (see analyses later).

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 conducted a supervised classification analysis by first drawing ≈200 training polygons with trees and 200 without trees in ArcMap. These polygons ranged in size from 2 m to 10 m in diameter and were selected to capture the variable spectral signature of treeless areas. Polygons were drawn around individual trees, as well as clumps of trees in high-density areas with no treeless pixels. These polygons were used to train the computer to generate a raster map of 2017 tree cover for the study area using a maximum likelihood classification algorithm (Maximum Likelihood Classification tool, ArcMap version 10.3). Whereas we used polygons for training data in order to capture the variable spectral signatures, we first validated the map at a much finer spatial scale (1×1 m pixel). To do this, 2 000 random points were generated across the study area for validation and each 1×1 m pixel was manually examined to see whether it should truly be classified (using the 2017 NAIP imagery) as either "Not Tree" or ""Tree". 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 with cover map values. Measures of agreement and disagreement between the random point values and the cover map values 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 and Millones 2011; Warrens 2015; Salk et al. 2018). 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 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 later), we analyzed our data at the 30×30 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 30×30 m sections around the study area in each classified cover category (for a total of 60 sections) and manually assessed tree cover using the 2017 NAIP imagery. At this 30×30 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.

Tree cover change analyses

To assess changes in tree cover from the 19th century to 2017 over our study area, the 19th century survey line segments were buffered by 15 m on either side and the resulting buffer polygons were sectioned into 30×30 m squares. These squares were overlaid with the 2017 classified map of tree cover and 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 (i.e., open to savanna or woodland), or contraction (i.e., woodland to savanna or open). In total, 2 051 polygons (each 900 m^2) across the study area were used for our analyses to assess changes in tree cover from the 19th century to present.

To test the hypothesis that woodland expansion is most likely to occur in areas of shallow soil depth with lower soil available water capacity (AWC), we used soil data from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (NRCS 2018). The SSURGO database, developed by a trained soil morphologist using aerial imagery, topographic interpretation, and field validation, is the highest-resolution soil map data available from the NRCS and was last updated in 2018 for our study area. These soil data are displayed as soil map units, which consist of one to three dominant soil types (referred to as *components*) and provide certain soil properties, such as soil AWC and soil depth, at the soil map unit and soil type level. Soil AWC is the amount of water that can be stored in the soil and be available for plants and is strongly correlated with herbaceous cover (Singh et al. 1998). As such, we assessed how woodland coverage changed across the study area in areas with soil map units characterized as low (< 10 cm), medium (≥ 10 cm and < 20 cm), and high (≥ 20 cm) soil AWC. Soil map units of low soil AWC areas generally have rocky, shallow soils (< 1 m depth; Table S2; available online at …) and support little herbaceous cover, whereas soil types with high soil AWC are characterized by deeper (> 1 m) and more fine-textured soils (see Table S2) that typically support high grass cover (Romme et al. 2003; Gascho Landis and Bailey 2005; Miller et al. 2008).

In order to assess whether changes in tree cover from the late 19th century to 2017 varied depending upon soil AWC, 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 AWC. As such, a P value ≤ 0.05 indicates that the amount of tree cover change varies depending on the soil AWC.

Sensitivity analyses

We assessed how sensitive our results were to 1) the spatial error among the 19th 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 m in each cardinal direction (N, E, S, W). Similar to analyses above, the four shifted shapefiles were then buffered by 15 m, sectioned into 30×30 m squares, and binned into the cover categories based on 2017 aerial imagery. We then analyzed tree cover change from the 19th century to 2017 using the four new shifted sets of 30×30 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 S3−S6).

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. Therefore, we assessed how the results vary depending on the size of the buffer used along the surveyor line to determine 2017 tree cover. In the analyses discussed earlier, we used a 15-m buffer and thus conducted the analyses based on 30×30 m squares. In order to test the effect of buffer size on the results, we conducted the same analysis with 5-m and 10-m buffers (e.g., 10×10 m squares and 20×20 m squares, respectively). These smaller buffers were used because surveyors were tasked with 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-m buffer size used earlier.

Results

We found evidence of significant woodland expansion and contraction across our study area. About 43% of all line segments categorized as open in the 19th century remained treeless, whereas about 39% of all 19_{th} century woodlands remained woodlands in 2017 (Fig. 2). Overall, reductions in tree cover nearly equaled increases of tree cover on the landscape. Sixty-one percent of 19th 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 19th century now have trees, with 23% classified as savanna and 34% classified as woodland.

The relative amounts of expansion compared with 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 m to 10 m and finally to 5 m, the reductions in tree cover increasingly outweigh expansions (Tables S7−S9, available online at …). For

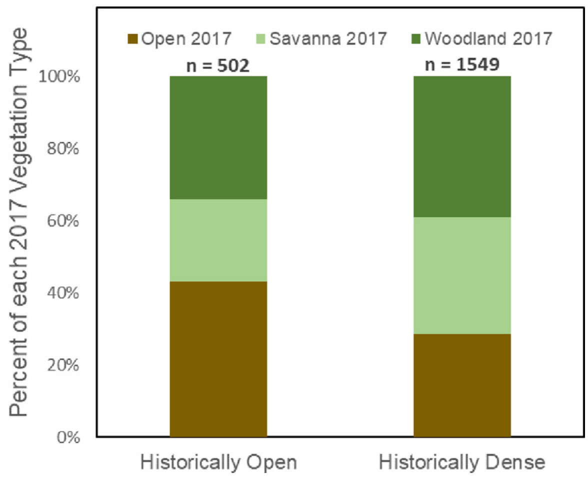

Fig. 2. Percent of 19th century open (treeless) and woodland areas that were classified as open (< 0.5% tree cover), savanna (≥ 0.5% and < 10% tree cover), and woodland (≥ 10% tree cover) by 2017. These tree cover changes were analyzed by buffering the survey lines by 15 m and sectioning these buffers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

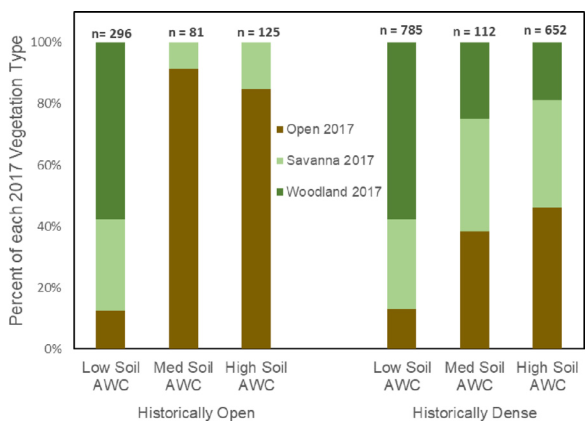

Fig. 3. Percent of 19th century open (treeless) and woodland areas that were classified as open (< 0.5% tree cover), savanna (≥ 0.5% and < 10% tree cover), and woodland (≥ 10% tree cover) by 2017 as a function of soil available water capacity (AWC) in centimeters. Soil AWC categories consist of "Low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

example, when using the smallest area of analysis (10 × 10 m squares from the 5-m buffer), we see only 45% of 19th century open areas that now have trees and 65% of 19th century woodland areas that have decreased below 10% tree cover. Thus, the 30 × 30 m analysis (from the 15-m 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 (χ^2 (10, N = 1945) = 700.59, $P < 0.001$; Fig. 3). Most expansion occurred in areas of low soil AWC, with 29% of all 19th century open areas in low soil AWC becoming savanna and 59% of these areas becoming woodland by 2017 (see Fig. 3). Areas with medium and high soil AWC experienced much less expansion and instead experienced significant reductions in tree cover. Respectively, 38% and 46% of 19th century woodlands became open in areas of medium and high soil water capacity, whereas only 13% of woodlands in areas of low soil AWC became 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 Fig. 3).

Discussion

Piñon-juniper expansion in the semiarid ecosystems of western North America has been well documented in the scientific literature from the early 1900s onwards (Johnsen 1962; Miller and Rose 1995; Belsky 1996; Miller et al. 2008; Romme et al. 2009). This expansion is often attributed to anthropogenic drivers, such as fire suppression and grazing, which has led to widespread tree removal treatments across the US Southwest (Romme et al. 2003; Redmond et al. 2013). Over the past 150 yr in our study area in southeastern Colorado, we documented evidence of expansion, as well as substantial contraction, counter to the general assumption that these woodlands have expanded in most areas. Importantly, changes in woodland cover were strongly associated with soil properties. 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 historic and 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 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 deeper and more fine-textured soils (i.e., areas of medium and high soil AWC). These areas of higher soil AWC are most commonly located in the uplands where grasses tend to be more dominant (Romme et al. 2003; Gascho Landis and Bailey 2005). 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.

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 and Garrison 2014). An account from a longtime local rancher and The Nature Conservancy property manager estimates as many 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 large amounts of timber cut for fencing, living structures, and corrals (Fig. 4). Notably, in this area there was no evidence of tree stumps, which is likely in part due to these settlers tearing the stumps out of the ground in the process of clearing a plot of land or farming. Despite a general local feeling that upland areas have expanded in tree cover, historical accounts by local ranchers in the region and physical evidence on the landscape (e.g., prevalence of axe cuts or wood used in living structure or fences) corroborates pervasive past woodcutting. Tree loss was greatest in upland areas of deep, high AWC soil that supports greater grass production and likely more frequent fires historically (Romme et al. 2009; Margolis 2014), which is where we originally predicted expansion to be most prevalent. However, we hypothesize that most people chose to settle, attempt to farm, and manage the land for ranching in these more productive upland soils, leading to woodland contraction.

Fig. 4. An abandoned homestead (left) and corral (right) at the center of an upland area (high soil available water capacity) that was historically a dense woodland.

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 encourage the establishment and persistence of trees (Floyd et al. 2004; Huffman et al. 2008; Shinneman and 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 and Bailey 2005), we know from local accounts that the rough, rocky, woodland areas of low soil AWC near canyon rims are not heavily grazed (JJ Autry; Chris Pague, personal communication). 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 past 150 yr in our study area in areas with rocky, shallow soil types (low soil AWC) is unlikely due to fire suppression or grazing. Whereas long fire return intervals and limited 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. Cool and wet climatic conditions over the past 150 yr at our study area promoted tree establishment as seen in other areas of the US Southwest (Barger et al. 2009; Shinneman and 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 m, 10 m, and 15 m. When analyzing the results with narrower buffers, we found woodland contractions to increasingly outweigh expansions (see Tables S1, S3, and S4). 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-m buffer (30×30 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 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. We also relied on the publicly available Soil Survey Geographic database (NRCS 2018) in assessing how changes in woodland extent varied with soil properties. This database is the most detailed level of soil mapping done by the NRCS and is developed by trained soil morphologists using aerial photographs and topographic interpretation in concert with field validation. This database is considered the most accurate available and has been used in many previous studies (e.g., Gu et al. 2013; Peterman et al. 2013), yet is still a derived product that relies on aerial imagery and, as a result, the soil map created may thus be influenced by woodland structure. From our observations working in portions of the study area, the soil maps did appear to effectively delineate areas with rocky and shallow soil types compared with the deeper upland soils, yet we did not quantitatively validate the soil maps.

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 areas with similar climatic conditions that were also heavily homesteaded, although similar dynamics may occur elsewhere. Previous documentations of piñon-juniper cutting during the incipient stages of Euro-American settlement (Bahre and Hutchinson 1985; Evans 1988; Ko et al. 2011) and more recent piñon-juniper cutting (Redmond et al. 2014) also occur 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 may also occur in piñon-juniper woodlands elsewhere.

Implications

Expansion and thickening in piñon-juniper woodlands due to the anthropogenic effects of fire suppression and grazing since

Euro-American settlement have been the leading paradigm in management of these ecosystems and led to widespread tree-removal treatments throughout much of their range (Romme et al. 2003; Redmond et al. 2013). Yet the results from our study do not support this widespread assumption of human-caused expansion and thickening for the juniper and piñon-juniper woodlands in southeastern Colorado. 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 past 150 yr. 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 past 150 yr across the settled, upland areas with deeper, higher AWC soils. Across the study area, tree increases nearly balanced 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 clear-cutting treatments in this region if the management is to restore historic ecosystem structure given documented contraction of these woodlands in upland areas of high soil AWC and the critical habitat woodlands provide for an array of wildlife species (Sedgwick 1987; Bombaci and Pejchar 2016). These results suggest caution in implementing treatments to restore ecosystem structure in piñon-juniper ecosystems 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 (Bombaci and 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. 2005; Hartmann et al. 2018) and recruitment failure (Redmond et al. 2015, 2012). 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 thinning treatments in rocky areas with low soil AWC is potentially more ecologically viable in southeastern Colorado, given that these areas have experienced increases in tree cover since the 19th century. However, these increases were most likely due to periodic cool and wet episodes of climate over the past 150 yr, 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 semiarid ecosystems across the western United States.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2020.07.001.

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