



Reconstruction of age structure and spatial arrangement of piñon–juniper woodlands and savannas of Anderson Mesa, northern Arizona

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Abstract

We examined age structure and spatial arrangement of piñon–juniper woodlands and savannas on six plots distributed across three different soil types in northern Arizona. These stands, as typical of many others in piñon–juniper ecosystems, have experienced increases in tree densities since the arrival of European settlers. The goal of this study was to reconstruct stand conditions in 1860, prior to livestock grazing, using stem-mapping to determine tree arrangement and tree-ring analysis to examine age structure and density. Ripley's $K(t)$, Ripley's $K_{12}(t)$, and Moran's I were used to analyze nearest neighbor distances, spatial association, and spatial autocorrelation, respectively. All sites have long term presence of juniper and piñon trees, with a pulse of establishment and survival occurring between 1860 and 1880 on basalt- and sandstone-derived soils. In contrast, limestone-derived soil had no pulse of tree establishment in 1860, but rather a steady increase in tree establishment since ca. 1700. Spatial arrangement of juniper trees in 1860 showed strong clumping patterns from a minimum distance of 15 m to all spatial scales. Piñon pine varied in spatial arrangement from clumping at all spatial scales to random at all spatial scales. Positive spatial autocorrelation was determined for age of juniper trees to a minimum distance of 21 m in current stand conditions, in contrast to no strong trends of spatial autocorrelation in 1860. By comparing the age structure and spatial results for the forest reconstruction of 1860 to current conditions, we were able to show variation among soil types in nurse tree association between piñon and juniper trees and unable to support the density dependent mortality hypothesis for these sites. Presettlement (1860) diameter distributions and basal areas can be used to develop structure control (BDq) prescriptions unique to each soil type to restore either savanna or woodlands condition. However, identifying one blanket prescription for tree reduction in piñon–juniper ecosystems of the southwestern United States, or even the Anderson Mesa landscape, would reduce the range of variability present in the form of woodlands and savannas.

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1. Introduction

The rapid rates of change in tree density and extent over the past century in many piñon–juniper ecosystems are often credited to the anthropogenic influence of livestock grazing and fire suppression (Cottam and Stewart, 1940; Blackburn and Tueller, 1970; Burkhardt and Tisdale, 1976; Tausch et al., 1981; Gottfried et al., 1995). Although not all areas have experienced increased tree density (Ffolliott and Gottfried, 2002) the large areas that have increased in density have caused concern for many ecologists and managers since piñon–juniper ecosystems cover a significant land mass in the western United States, estimated at nearly 30 million hectares (West, 1999a). In addition, this increase in tree density and extent has led to many undesirable effects: an increase in rates of soil erosion (Carrara and Carroll, 1979; Price, 1993), a decrease in understory herbaceous cover and diversity available for forage (Pieper, 1990; Tausch and West, 1995), a change in hydrological processes (Wilcox, 1994; Baker et al., 1995), and in some regions an alteration of the fire regime due to a change in fuel structure (West, 1999b; Miller and Tausch, 2001).

The typical response to these changes in piñon and juniper tree densities has been wholesale removal of the trees from the landscape (Arnold et al., 1964; Clary et al., 1974; Tausch and Tueller, 1977). This causes further major disruption to the system and eliminates the trees, which provide microhabitat for a variety of plant species, cover for wildlife, and nesting for birds; therefore, it is not an appropriate treatment for all areas that have experienced increased canopy cover. More recently, treatments are being implemented that restore a certain density of trees thought to be consistent with presettlement conditions (Jacobs and Gatewood, 1999; Brockway et al., 2002; Jacobs and Gatewood, 2002). All too often, however, we have only a vague understanding of those conditions.

Reconstructing stand age structure provides a reference point to guide treatments and long-term management of forested systems that have been altered by anthropogenic means (Foster et al., 1996). Information from historic age distributions can support inferences pertaining to temporal patterns of tree establishment, regeneration patterns, and disturbance histories of presettlement forests (Lorimer, 1977; Mast et al., 1999; Bailey and Covington,

2002). Age structure can be extended when dead trees are included in the analysis (Johnson et al., 1994; Mast et al., 1999). Incorporating the age of presettlement trees with their spatial location allows for inferences concerning potential changes of spatial patterns in forests over a given period of time (Frelich and Graumlich, 1994; Antos and Parish, 2002).

Although reconstruction of fire occurrences on Anderson Mesa is beyond the scope of this study of forest structure it is important to recognize the potential variability of fire. Floyd et al. (2000) found a fire return interval of 400 years, characterized by stand-replacing fires in the piñon–juniper woodlands at Mesa Verde National Park, Colorado, USA, by constructing time since fire maps. These long fire intervals are driven partially because of rocky soil and highly dissected topography. Another study on the Colorado Plateau determined the fire return interval in a *Juniperus osteosperma*/*Pinus edulis* stand to be approximately 25 years (Despain and Mosely, 1990). A recent review of all the literature pertaining to fire in piñon–juniper concluded little to no evidence exists documenting a low intensity, surface fire regime (Baker and Shinneman, 2004). However, Romme et al. (2003) hypothesized that a wide range of disturbance regimes are possible in the piñon–juniper ecosystems of the Colorado Plateau, but that much research is needed to identify distinguishing characteristics of different fire frequencies. Because of a wide range of possible fire regimes across the landscape it is important to consider other potential indicators of fire regime frequency, such as topography, soil type, and change in forest structure (Romme et al., 2003).

When determining historic forest structure, it is also essential to examine the variation in vegetation types that are controlled by soil influences. The pattern of woody plants and grass distribution is highly influenced by the topography and edaphic features of the landscape (Archer, 1994). Throughout the southwestern United States, piñon–juniper woodlands are diverse, containing assemblages of various species of piñon and juniper trees. According to Moir and Carleton (1987), piñon–juniper woodlands of the Southwest feature 70 plant associations and upwards of 280 ecosystem types. Work by Thatcher and Hart (1974) in a piñon–juniper relict site shows a link between grass or tree cover and corresponding soil types.

Forest reconstruction to establish reference conditions for piñon–juniper ecosystems is a critical part of the restoration process. Our study began this process by reconstructing age structure and spatial arrange-

ment of piñon–juniper woodlands and savannas of Anderson Mesa prior to 1860, the estimated time of arrival of livestock (Carlock, 1994). We assessed changes and patterns in age structure and spatial

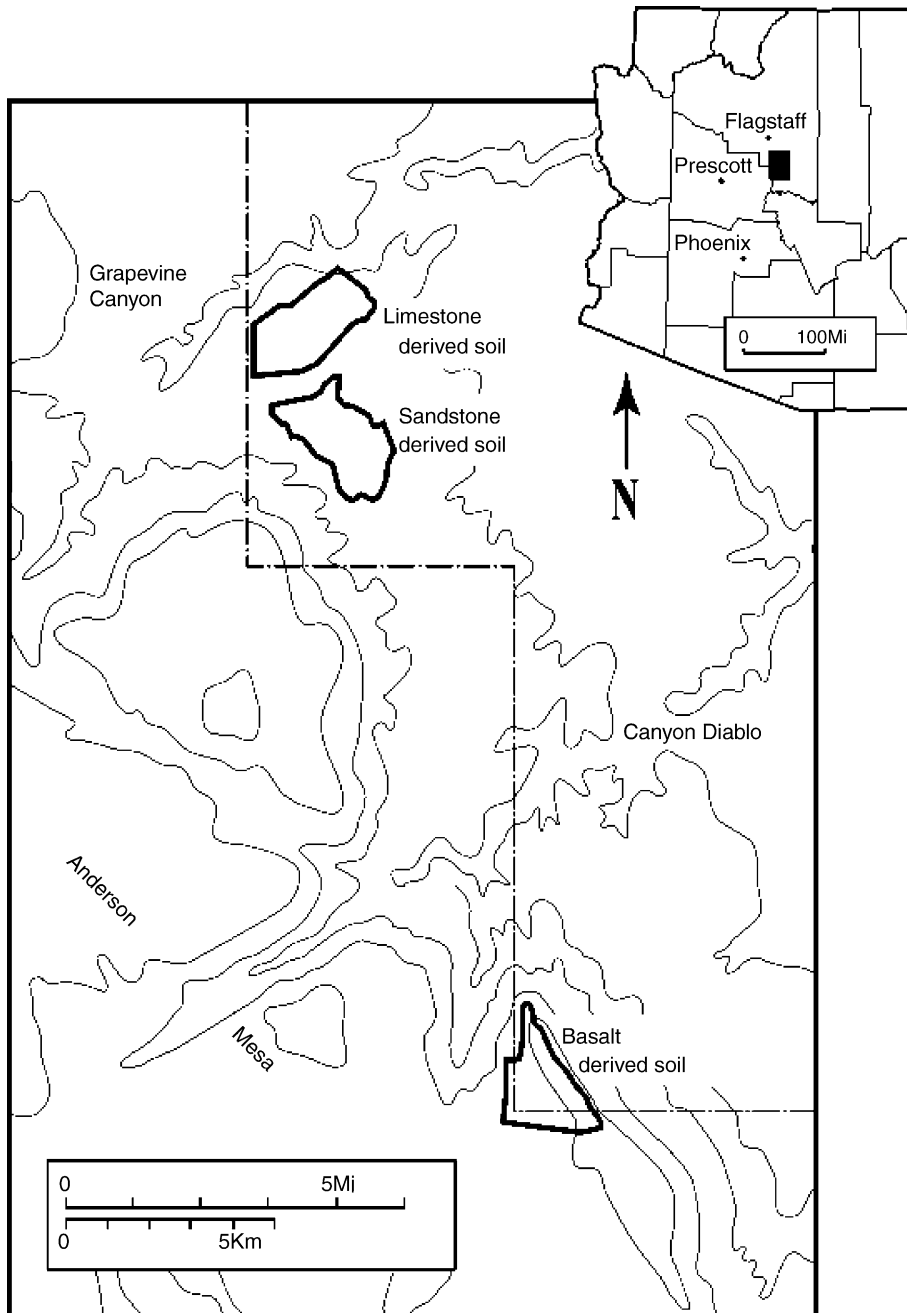


Fig. 1. Map of the study areas on Anderson Mesa, 150 km south east of Flagstaff, AZ.

arrangement across three different soil types. Prescriptions can be developed from this information that are essential to scientifically-based restoration treatments and long-term management.

2. Methods

2.1. Study area

The study areas are located on Anderson Mesa, approximately 150 km southeast of Flagstaff, Arizona (Fig. 1). We chose three different soil types representing common parent material types on Anderson Mesa (Taylor, 1983) (Table 1). One plot is located on private property owned by the Flying M Ranch, a member of the Diablo Trust Collaborative Land Management group, and the other two soil types are located on Arizona State Trust Land, just below the rim of Anderson Mesa. All sites were chosen for reconstruction in part because their remote locations have resulted in little to no previous fuel wood harvesting, indicated by a lack of stumps from cut trees. Choosing sites undisturbed by human wood harvesting ensured that evidence from presettlement woodlands was not missing, allowing for a complete reconstruction of these tree populations Fig. 2.

2.2. Field data collection

In 2001 and 2002 we randomly chose two plots within each soil type in which to reconstruct age structure and spatial arrangement. At each soil type, one of the plots was 1.56 ha (125 m × 125 m) and the other plot was 0.78 ha (125 m × 62.5 m). According to Despain (1989), to accurately date juniper trees it is best to take a cross-section of the stem for examination due to the fact that Utah juniper trees do not grow concentrically and produce many lobes and stems. All

juniper and piñon trees were felled with chainsaws, and a 3–10 cm wide disc was cut from the bole as close to the ground as conditions safely allowed (Tausch and West, 1988). We originally planned to core piñon trees since they can be readily cross-dated, however, an *Ips pini* outbreak killed the majority of the piñons and thus we decided to fell the trees to obtain a reliable pith date. Juniper and piñon seedlings and small saplings were cut using lopping shears as close to the ground as possible. In areas with abundant piñon seedlings the trees were surveyed and automatically placed in the first 20-year age class. All tree diameters were measured at root collar to the nearest half centimeter; crown radii and tree height were measured on a subsample of trees to the nearest tenth meter.

All trees, living and dead, in the plots were mapped using a Criterion Laser mounted on a tripod (Laser Technology, 1997). The southwest corner of the plot was the starting station for mapping. All distances were recorded to the nearest half centimeter, and all the azimuths were recorded to the nearest minute. Distance and azimuth measurements were converted to a Cartesian coordinate system for analysis.

2.3. Laboratory techniques

All piñon and juniper discs were returned to the lab for processing. They were sanded with progressively finer grits of sandpaper. We counted rings for each juniper tree cross-section using a binocular microscope. Great effort was made to avoid counting false rings by counting on the radius of the cross-section that exhibited the most uniform growth characteristics (Tausch and West, 1988); however, juniper samples could not be cross-dated to identify missing rings due to limitations of time, cost, and difficulty (Gottfried et al., 1995). Piñon pine samples were visually cross-dated, using standard methods (Stokes and Smiley, 1968). After determining ages, trees were placed in

Table 1
Elevation and soil characteristics for each site in the piñon–juniper research areas

Soil type	Elevation (m)	Maximum slope	Available water	Hazard of erosion	Permeability
Basalt-derived	2073	<8%	Medium	Slight	Very slow
Sandstone-derived	1920	2–15%	High	Moderate	Slow
Limestone-derived	1920	<8%	Very low	Slight to moderate	Moderate

Taylor, 1983. Available water: capacity of the soil to hold water to be used by plants. Hazard of erosion: the probability of accelerated erosion after soils have been exposed. Permeability: quality of soil that allows water to move downward through the soil column.

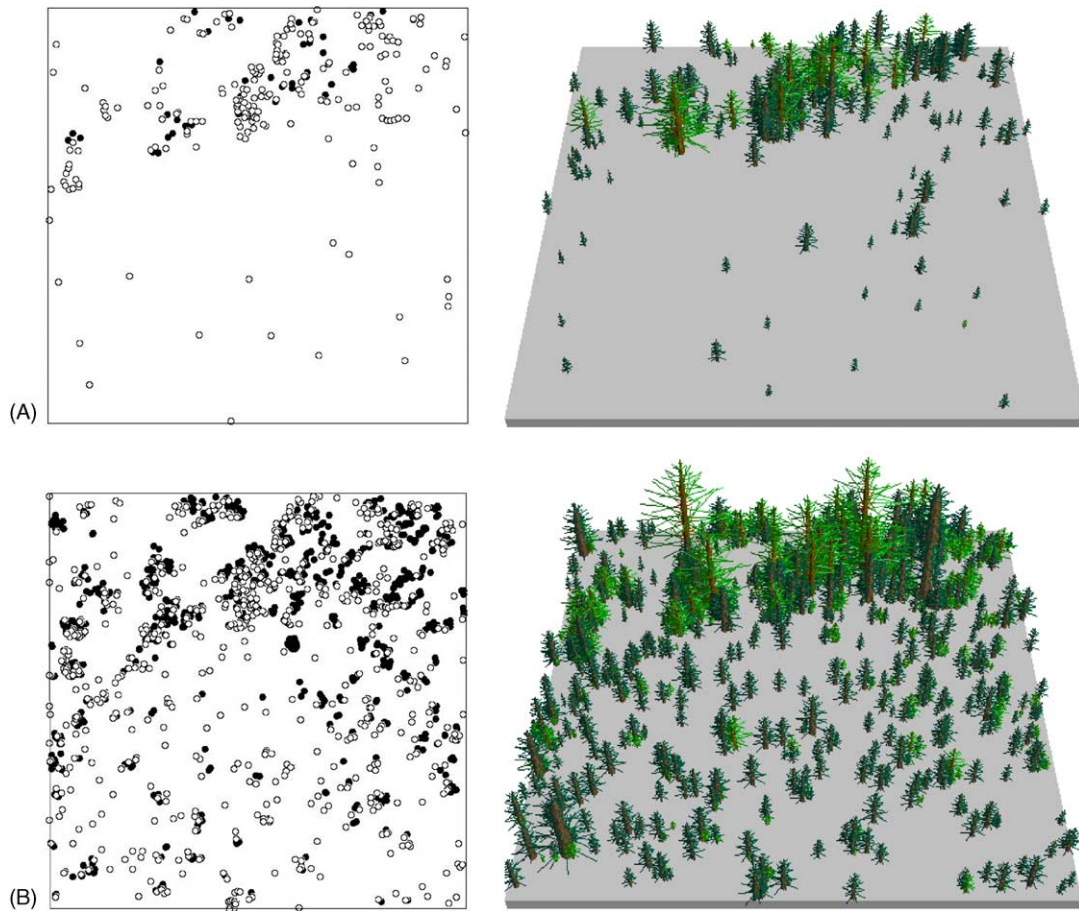


Fig. 2. (A) Stem map and tree visualization of piñon–juniper trees on basalt-derived soil in 1860 (top). (B) Current stem map and tree visualization (bottom) (125 m \times 125 m). Open circles and black trees represent *Juniperus osteosperma*, and closed circles and gray trees represent *Pinus edulis* on the stem map and tree visualization, respectively.

twenty-year age classes for analysis. To reconstruct tree diameter of specimens established before 1860, their diameters were measured inside the bark at the ring that represented the year 1860 on all trees from the 62.5 m \times 125 m plots. Using the regression relationship between the outside diameter and the inside diameter we were able to predict the inside diameters for trees on the larger plots (125 m \times 125 m). To aid in tree reconstruction, we developed a bark thickness equation specific to each soil type for both tree species by measuring bark thickness on a random distribution of diameter classes in order to regress the two variables, bark thickness and diameter at root collar ($r^2 = 0.73, 0.85, 0.92$ for limestone,

basalt, and sandstone-derived soils, respectively). Canopy cover as a percent of total plot size was estimated from crown diameter for all soil types in 1860 and 2002. Since juniper trees tend to grow in clumps we assumed 20% canopy overlap for all sites.

2.4. Statistical analysis

We analyzed piñon and juniper spatial patterns using Ripley's $K(t)$ and Ripley's $K_{12}(t)$ and measured piñon and juniper tree spatial autocorrelation using Moran's I , for both the 2002 and 1860 stands (Ripley, 1981). Dead juniper trees that contained at least 140 rings were assumed to be alive in the analysis of 1860

spatial arrangement. Analyses were performed using Duncan's spatial software (Duncan, 1990). We did all tests using increasing step size of 1 m (t) for up to a 31 or 62 m distance for each stem. These distances are half the length of the shortest side of the plot and were used to reduce the error induced by edge effect (Boots and Getis, 1988). The remaining edge effect was adjusted through the use of a toroidal correction factor.

Ripley's $K(t)$ and Ripley's $K_{12}(t)$ for current and historical tree species location and association, respectively are graphed by plotting the derived sample statistic $L(t)$ and $L_{12}(t)$, (Haase, 1995; Wells and Getis, 1999). Positive values that appear above the upper confidence interval represent plants arranged in clumps or that two species are aggregated; negative values that appear below the lower confidence interval represent regularly dispersed plants or that the two species are segregated (Skarpe, 1991). We calculated Moran's I for tree age (years) and tree size (diameter at root collar) and plotted the results as standard normal deviates, $z(d)$, for each distance class (t) at a significance level of 0.05 (Friedman et al., 2001).

Significant positive and negative spatial autocorrelation occur when the standard normal deviate is above or below 1.96 and -1.96 , respectively (Duncan and Stewart, 1991). Positive spatial autocorrelation occurs when trees at a distance of t are similar in age or size and negative spatial autocorrelation when trees at a distance of t are dissimilar in age or size.

3. Results

3.1. Age structure and density

Under current conditions, Utah juniper was the dominant tree species at each site, occupying 89–99.5% of the basal area (Table 2). Total current tree density on basalt and limestone-derived soils are equal and more than twice as high as tree densities on sandstone-derived soil. The highest basal area and canopy cover is currently found on limestone-derived soil (Table 2). Historical stand structure varied among soil types with tree densities approximately equal on basalt- and sandstone-derived soils. Limestone-

Table 2

Species density, canopy cover, basal area in m^2/ha (based on diameter at root collar), QMD in cm (based on diameter at root collar), total evidences of mortality and total number of juniper samples unable to be dated to pith for all sites, current and presettlement

	Trees/ha	Lacking pith	Canopy cover	Dead (2002)	QMD	BA
2002						
Basalt-derived						
Juniper	463	14	29.9	7	26.9	28.6
Piñon	390	0		7	5.4	1.2
Sandstone-derived						
Juniper	321	56	33.8	33	38.1	34.5
Piñon	20	0		0	10.5	0.1
Limestone-derived						
Juniper	565	118	44.3	9	34.5	53.0
Piñon	289	0		17	10.8	2.7
1860						
Basalt-derived						
Juniper	94		4.5		25.8	4.7
Piñon	16				6.0	0.3
Sandstone-derived						
Juniper	119		11.5		34.5	10.6
Piñon	3				5.0	0
Limestone-derived						
Juniper	217		14.7		20.2	8.9
Piñon	29				8.1	0.17

derived soil contained average densities that were twice as high as the other stands.

Starting in the 20-year period between 1860 and 1880, there is a distinct pulse in the establishment and survival of Utah juniper trees on both the sandstone- and basalt-derived soils that has continued at high levels until the present (Fig. 3). These stands showed low levels of continuous Utah juniper tree establishment and survival over the past several hundred years, then a marked increase after 1860. The oldest evidence of juniper trees at these sites established ca. 1494 and 1405 for basalt- and sandstone-derived soil, respectively. The age structure of the stand located on limestone-derived soil differed from the others, showing a marked increase in trees starting 300 years ago (Fig. 3). A steady increase of tree establishment at this site continued to the present. The oldest juniper tree on this soil type dated to approximately 1411.

In contrast to juniper trees, establishment of piñon pine occurred at different rates across various soil types. Piñon pine trees at all sites were not as long lived as juniper trees with the oldest piñon evidence establishing in 1645 on basalt-derived soil, 1751 on sandstone-derived soil, and 1549 on limestone-derived soil. Basalt- and limestone-derived soils both showed establishment of piñon pine for at least the past 300 years (Fig. 3). Trees on both soil types showed an increase in density occurring around the start of livestock grazing approximately 140 years ago, as compared to the prior decades. The highest rates of piñon pine establishment started in the period between 1940 and 1960. Piñon pines growing on sandstone-derived soil were present in the stand at extremely low numbers and showed no clear trend (Fig. 3).

Skeletons of dead trees, both piñon and juniper, were scattered throughout all plots. Dead evidences, either still standing or lying on the ground, ranged from 2–37 stems/ha for juniper trees and 0–14 stems/ha for piñon pine based on our plots (Table 2). None of these dead evidences were those created by *Ips pini* infestation. Sandstone-derived soil showed the highest level of dead juniper trees, comprising 3–10% of the total juniper trees with an average drc of 35.0 cm. The highest densities of dead piñon pine were on limestone-derived soils, comprising 4.4–6% of the total piñon trees/ha, with an average drc of 8 cm (Table 2). The range of drc for dead juniper trees across all sites

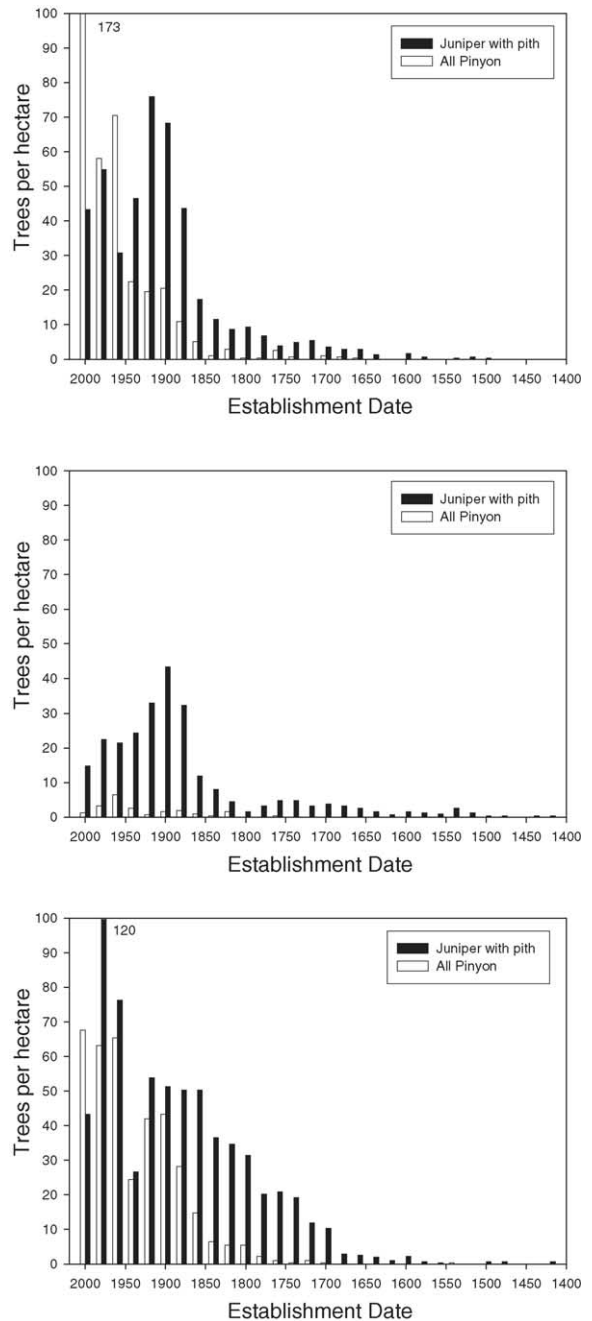


Fig. 3. Current piñon–juniper age structure for basalt-derived soil (top), sandstone-derived soil (middle), and limestone-derived soil (bottom) in Northern Arizona. Bars represent 20-year age classes.

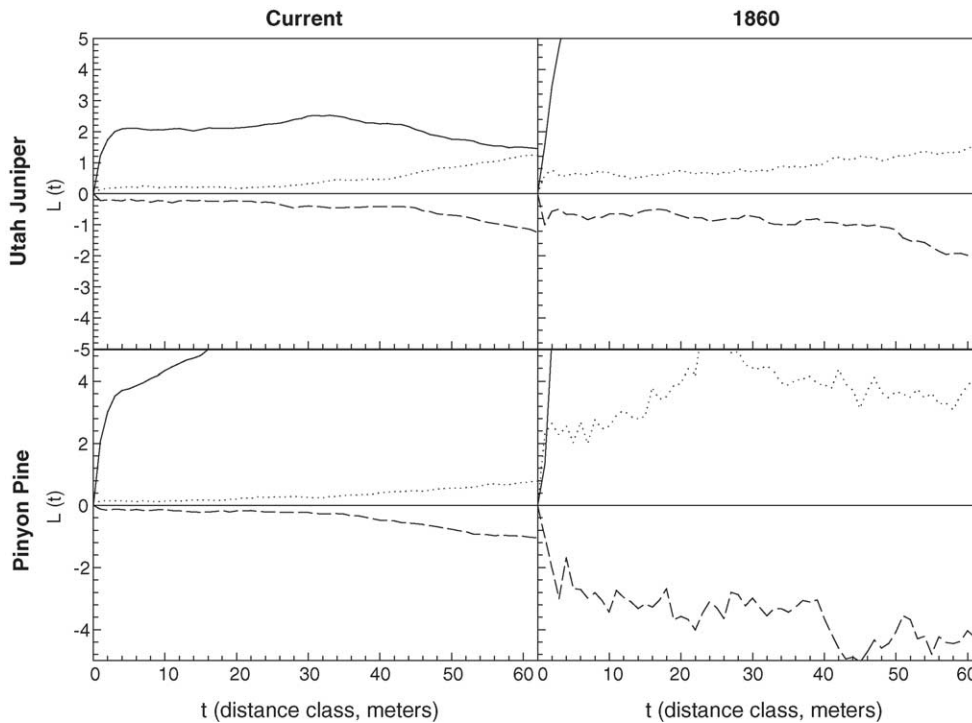


Fig. 4. Ripley's $L(t)$ plotted against t (distance class) for Utah juniper and piñon pine on basalt-derived soil ($125 \text{ m} \times 125 \text{ m}$). The left column is the current spatial arrangement of trees and the right column is the 1860 spatial arrangement of trees. Dashed lines are the upper and lower confidence intervals and the solid line represents $L(t)$.

was 0.25–110.5 cm and for piñon the size range was 0.5–32.5 cm.

3.2. Spatial arrangement

Examination of tree arrangement in 1860 indicated clumping for juniper trees at all spatial scales on basalt- and sandstone-derived soils (Fig. 4). On limestone soil, spatial arrangement of juniper trees was clumped up to distances of 13–45 m and random at larger distances. Ripley's $K(t)$ statistical assessment of presettlement piñon pine on all soil types in 1860 was not feasible because of too few trees for analysis.

Utah juniper trees on all three soil types currently displayed clumped distributions at all spatial scales as did piñon pine arrangement on basalt-derived soil (Fig. 4). In contrast, piñon pines found on sandstone-derived soil were randomly distributed at all scales. Limestone-derived soil represented an intermediate pattern between random and clumped, with clumping

at distances of 10–40 m and random distributions at greater scales.

Ripley's $K_{12}(t)$ was used to compare the spatial association of piñon trees versus juniper trees at two of the sites. Analysis was limited on sandstone-derived soil because of too few piñon trees. The 1860 associations were characterized by a positive relationship at distances of 4–10 m for both basalt- and limestone-derived soils (Fig. 5). Current piñon and juniper trees on the basalt-derived soils showed positive association up to a distance of 38 m and random association at greater distances (Fig. 5). One plot on limestone-derived soil displayed positive association between the current piñon and juniper trees up to distances of 10 m.

In 1860 there were only a few instances of positive spatial autocorrelation for Utah juniper ages at small distance classes (<10 m) (Fig. 6). Beyond these occurrences, the analysis of presettlement arrangement indicated largely random associations for both piñon and juniper trees.

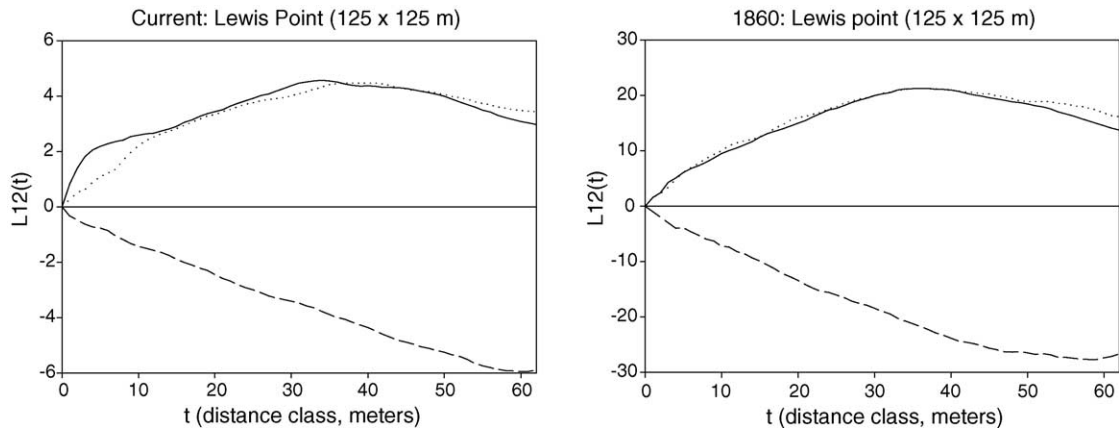


Fig. 5. Spatial association between piñon pine and Utah juniper on basalt-derived soil. Current association on the left and 1860 association on the right. Dashed lines are the upper and lower confidence intervals and the solid line represents $L_{12}(t)$.

Current Utah juniper tree ages were positively spatially autocorrelated on all three 1.56 ha plots up to a minimum distance of 21 m (Fig. 6). Using diameter to determine the level of autocorrelation for juniper trees indicated the same pattern of development as age only on limestone-derived soils; other soil types exhibited no distinct pattern. For piñon pine, Moran's I showed positive spatial autocorrelation of tree ages on basalt-derived soil consistently at distances of <4 m, with an intermixing of positive and random autocorrelation at larger distances (Fig. 6). Piñon pine on the other soil types did not show consistent positive spatial autocorrelation.

4. Discussion

In our reconstruction of past forest structure we used dead material to help assess presettlement densities and arrangement in juniper; however, because of difficulty in cross-dating juniper trees, we were not able to obtain an extended juniper age structure. Another difficulty in the process of assessing the establishment date of juniper trees was the presence of *Phellinus texanus* Murr. rot (Gilbertson and Lindsey, 1975). This rot tended to affect older and larger trees within our study areas with only 6.25–21% of total trees affected younger than 140 years. This ensured that the identified regeneration pulses since settlement were mostly

unaffected by rot, with the vast majority having center dates. Although not all trees dated to establishment, due to either death or rot, we were able to obtain accurate spatial locations at the time of European settlement. It is important to note that our age structure diagrams should not be used to deduce multiple-century patterns of regeneration, because there are gaps created in this presettlement structure that could be caused by trees lacking pith and dead wood and because of the potential for missing cohorts of smaller trees (Johnson et al., 1994).

4.1. Age structure and density

Tausch et al. (1981) determined that the highest level of juniper species establishment throughout the Great Basin occurred from 1870–1920, the period most impacted by European settlers. The results from our study agreed with those findings, with a large pulse of establishment increasing tree density across all soil types as compared to 1860 densities. Sites characterized by Tausch et al. (1981) were dominated by piñon; in contrast, all of our study sites were clearly dominated by juniper in both number of trees/ha and in amount of basal area each species comprised. Although their data is from the Great Basin it reflects the widespread nature of increasing tree numbers at the time settlers arrived in the western U.S. In both studies it is difficult to determine the exact density of historical trees because it is impossible to reconstruct

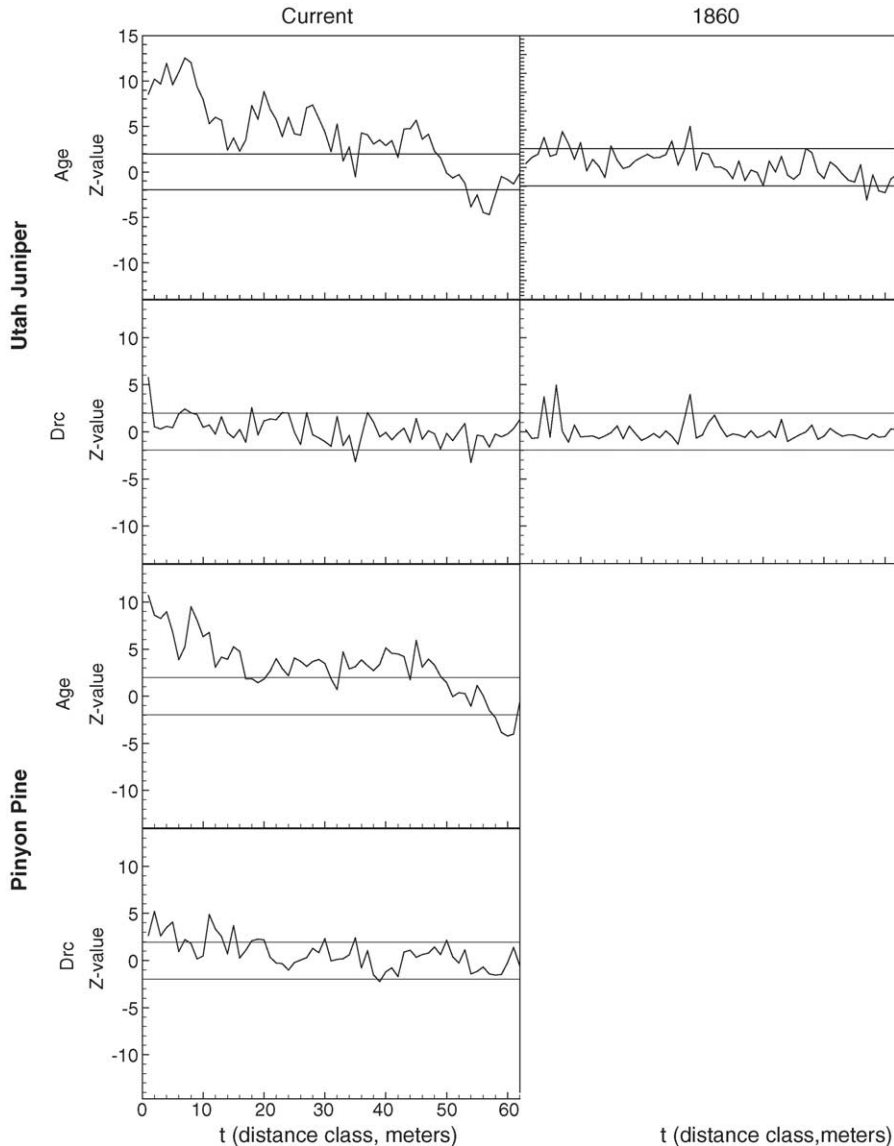


Fig. 6. Spatial autocorrelation correlograms for basalt-derived soil (125 m × 125 m). Horizontal lines indicate the 0.05 significance level.

seedlings and saplings. Typically they occur in high densities and experience higher rates of mortality and decay. However, the occurrence of a pulse indicates that ecosystem dynamics changed from previous times to allow for greater numbers of trees to survive into older age classes. Although the role and frequency of fire is uncertain, it is known that livestock entered the area concurrently with the pulses, suggesting that grazing reduced grasses' ability to compete with the trees.

West (1999a) claimed that many piñon–juniper areas throughout the Intermountain West formerly were savanna systems and that many fewer woodlands existed. He defined savannas as grass-dominated ecosystems that have a woody overstory with a continuous grass understory and woodlands as tree dominated systems with a discontinuous grass understory. Other savanna ecosystems (non piñon–juniper) define the parameters more narrowly, with

savannas containing 5–30% canopy cover, woodlands containing 30–80% canopy cover, and all cover greater than 80% as forest (Heidorn, 1994). However, in piñon–juniper ecosystems Milne et al. (1996) determined the critical value of tree cover of 59.3% at which woodlands change abruptly from a fragmented collection of small patches of trees to a network of connected canopies. For piñon–juniper ecosystems, therefore, a more appropriate range for woodland canopy cover in the Southwest might be from 30–60%. In 1860, canopy covers on all soil types from our study fell into the savanna category, ranging on average from 4.5% on basalt-derived to 11.5% on sandstone-derived soil, and 14.7% on limestone-derived soil. However, by 2002 canopy cover increased so that all sites had neared or crossed the threshold into woodland—basalt-derived soil with canopy cover of 29.9%, sandstone with 33.8%, and limestone-derived with 44.3%. None of these stands, currently or historically, represent piñon–juniper forest conditions, confirmed by the classification of Romme et al. (2003), which asserts that piñon–juniper forests typically have not experienced a change in tree density since the time of settlement. Additionally, none of the sites have extremely rocky soil nor is the topography such that would prevent the spread of fire, another potential indicator of piñon–juniper forest (Romme et al., 2003).

Although all 1860 stands fit the savanna category according to canopy cover, tree densities and clumping patterns place them differently on the gradient between savanna and woodland. In 1860, the limestone-derived soil had twice the tree density of other plots and also smaller, more evenly distributed clumps than other plots as demonstrated by clumping from 13–45 m in 1860. These characteristics identify the limestone-derived soil sites as being closer to the woodland end of the gradient before settlement, which had a less contiguous understory (Romme et al., 2003). In contrast the basalt- and sandstone-derived soils averaged 110 and 122 trees/ha in 1860, respectively, which were found in larger clumps located on a smaller portion of the plot as demonstrated by clumping at all spatial scales in 1860. Theoretically, the lower tree densities found in clumps of greater size allowed for a much larger and more contiguous grass community, more indicative of a savanna-like system.

Disturbance history, in addition to edaphic features, is an important factor in controlling stand structure in the piñon–juniper ecosystem (Romme et al., 2003). The primary natural disturbance factors affecting tree densities in savanna ecosystems are fire, drought, and herbivory (van Langevelde et al., 2003). Large quantities of dead material, as a percent of the total trees, located on sandstone-derived soil type could have been indicative of more recent disturbance(s), either drought or fire. However, this soil type was the only one containing evidence of fire scars on juniper trees (personal observation). This perhaps implies that fire is a factor in conjunction with edaphic features, in maintaining stand structure in piñon–juniper ecosystems on Anderson Mesa (Miller and Tausch, 2001).

4.2. Spatial arrangement

On basalt- and sandstone-derived soils, juniper trees were clumped at all scales, both historically and currently, indicating the presence of very large clumps in 1860 that are still evident on stands today. On limestone-derived soil, the change from random at larger scales in 1860 to the current clumping at all spatial scales indicated that this site was comprised of smaller sized clumps, and through time, encroaching trees filled in the interspaces, causing clumps to reach maximum spatial scales. This differed from the findings of Martens et al. (1997), which showed current Utah juniper clumped at a scale of 2–5 m, indicating very small clumps of trees.

Current piñon pine varied in its pattern of spatial distribution and, due to limited sample size, little was determined about 1860 spatial arrangements. However, the lack of piñon pine in these plots, especially the sandstone-derived plots, indicated that piñon pine had more recently become an increasingly important part of the structure at these sites.

Physiological characteristics of juniper trees, such as drought tolerance and ability to obtain water from shallow soil, allow them to establish in harsh interspaces in piñon–juniper ecosystems (Nowak et al., 1999). In comparison, piñon pine is typically more highly dependent on microhabitat created by a nurse plant and will rarely establish in interspaces (Callaway et al., 1996). Microclimate provided by nurse plants significantly reduces temperature and increases moisture, which can allow for successful piñon

seedling establishment. Padien and Lajtha (1992) determined that piñon seedlings showed a trend toward a more positive association with established juniper canopies.

Trees on basalt-derived soils best followed this nurse tree theory of establishment. Currently trees of both species were clumped, and there was positive association between species, indicating that piñon and juniper trees could be found growing together in clumps up to distances of 27 m. Nurse tree colonization was consistent with the Morans *I* analyses, which showed a shift from no autocorrelation in 1860 to positive autocorrelation with age of both piñon and juniper trees in current stand arrangement. This indicated that recently established trees were growing in clumps of similarly aged trees. This hypothesis was further supported by the age structure. A large pulse of piñon pine established during the past 60 years; these piñon trees appeared to be responding to the pulse of juniper trees that started post-1860. Juniper trees were able to colonize open spaces in the community, and after a lag time of approximately 60–80 years became large enough to alter the microclimate beneath their canopy. As a result, starting approximately 60–80 years ago, piñon trees had larger amounts of growing space available for establishment and thus could more rapidly colonize the site.

According to these principles it would seem logical that the stand on sandstone-derived soil should have large amounts of younger piñon pine responding to the pulse of post-1860 juniper, and the growing space it provided, but it did not. These plots had only a total of 14–25 piñon trees/ha. The lack of piñon pine could be attributed to the level of erodability of this soil type, which was greatest among the three series (Table 1) and could be detrimental to establishment of piñon pine.

Limestone-derived soil type differed from the others in the long-term occupation of the site by both piñon and juniper trees. The dynamics seemed to represent increasing tree density in a woodland, not colonization of the grass understory in a piñon–juniper savanna. In contrast to the other stands, substantial microsite under juniper trees had long been available for piñon trees to use for establishment. The colonization of these microsites was evident by the large number of older piñon trees and the positive association found historically between the piñon and juniper trees.

5. Management implications and strategies

One goal of restoring piñon–juniper ecosystems is to prevent the occurrence of irreversible changes so that they do not cross thresholds that would lead to trajectories outside their natural range of variability (Laycock, 1991; SER, 2002). It is essential to develop reference conditions to do this properly (White and Walker, 1997; Stephenson, 1999). This study shows that forest reconstruction is necessary at various locations throughout the landscape, such as various soil types, aspects, elevations, and topography, in order to capture the heterogeneity in stand structure typically represented by a gradient ranging from savanna to woodland. Identifying a blanket prescription for piñon–juniper ecosystems of the southwestern United States or even the Anderson Mesa landscape would reduce the range of variability present in the form of woodlands and savannas.

Restoration of the structure in piñon–juniper ecosystems on the Anderson Mesa landscape first will require thinning, primarily of juniper trees, regardless of whether the site was formerly savanna or woodland. However, not all trees establishing after 1860 should be removed. A component of younger trees needs to be retained to match the uneven-aged distribution of presettlement piñon–juniper ecosystems, which showed few gaps in establishment across multiple centuries.

Selection silviculture is a valuable tool for meeting uneven-aged forest objectives, which prioritize long-term forest cover, biodiversity, and sustainability (O'Hara, 1998). Structure control is one method of uneven-aged management, based on a BDq: basal area, maximum diameter, and *q*-ratio, that achieves a sustainable distribution of ages/sizes (Nyland, 1996). The *q*-factor produces a reverse J-shaped distribution because it is the ratio of trees in a diameter class to number of trees in the next largest diameter class; as diameter classes get smaller, number of trees increases (Bailey and Covington, 2002). The ultimate goal of using a BDq or any of several other approaches is simply to regulate standing tree density distributions. This management technique can be used to meet any objectives (e.g., wildlife habitat) where specific structural goals are required.

The overarching landowner goal that prompted this research was to restore presettlement structure to

piñon–juniper woodlands and savannas. The plan for executing restoration treatments will be based on multi-aged group-selection silviculture and, specifically, a BDq that mimics the reverse-J-shapes of

juniper diameter distributions in 1860. BDq equations were developed for juniper trees at all three soil types due to the variation in site productivity and stand dynamics (Fig. 7). Equations were only developed for

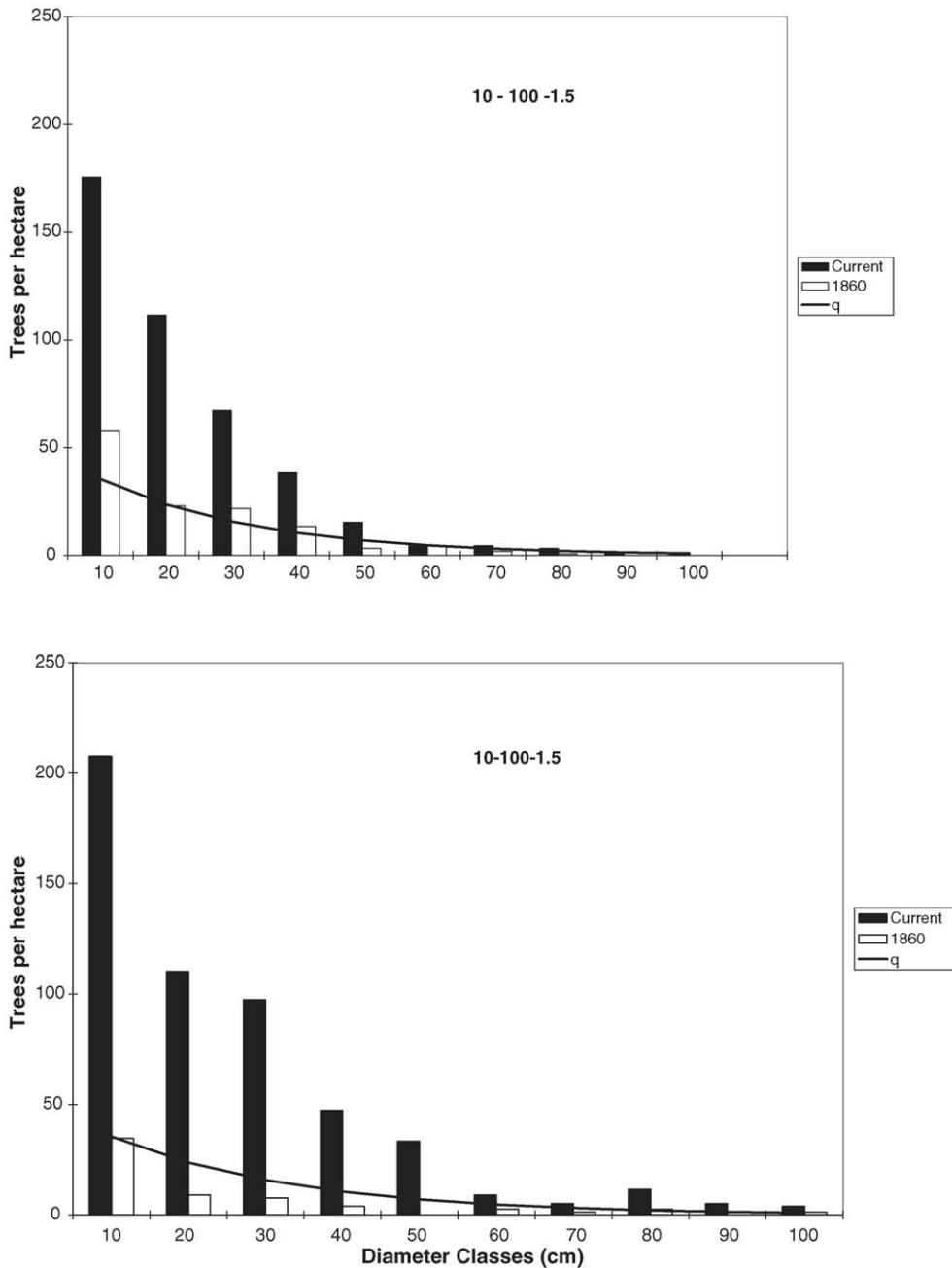


Fig. 7. Utah juniper diameter distribution in 10 cm classes for current trees (black bars) and 1860 trees (white bars) for basalt-derived soil, with the overlaid BDq line suggested for multi-aged management. Full-sized plot (125 m × 125 m) on top and half plot (62.5 m × 125 m) on the bottom.

juniper trees because they comprise the vast majority of basal area and encroachment in the treatment areas of Anderson Mesa.

Maximum diameter usually represents the size at which trees are harvested, but in this management setting trees over the maximum diameter (100 cm) are not considered for harvest because of their value in the ecosystem. The basal area of trees >100 cm was subtracted from the basal area of trees establishing before 1860. The q -factor was developed to fit as closely as possible the diameter distribution of trees present in 1860. A BD q was developed first by using the whole plots (125 m \times 125 m) that had predicted diameters for the 1860 distribution. The determined BD q was then verified by plotting it on the half plot (62.5 m \times 25 m) that had actual diameters from 1860. The fit was then adjusted to better fulfil diameter distributions of both plots within each soil type.

BD q 's of 10-100-1.5 for basalt-derived soil, 20-100-1.25 for sandstone-derived soil, and 30-100-1.4 for limestone-derived soil using 10 cm diameter classes were determined to be the closest approximation to structural conditions in 1860 (Fig. 7) from the half plots. The full sized plots in 1860 in all cases had higher levels of basal area than the half plots. The q -factor was developed by fitting the curve between the two data sets. Land managers can use their best judgment as to what conditions were historically appropriate for the stands that they manage, or determine a desired future structure, and choose a BD q that best meets these objectives. Most importantly, managers should vary intensity of thinning treatments across the landscape to account for variation in presettlement trees/ha due to changes in soil type, aspect, and elevation and to mimic spatial patterns.

In addition to thinning, fire has often been used as an important tool for restoring ecological function to woodland and Savanna ecosystems (Covington et al., 1997; Peterson and Reich, 2001). However, caution should be exercised if fire is to be used as a tool for restoration work in piñon–juniper ecosystems, especially concerning the frequency of fire use, because the role of fire is poorly understood throughout the Intermountain West (Baker and Shinneman, 2004); what is known indicates considerable variation throughout the range of piñon–juniper ecosystems (Miller and Tausch, 2001). Although West (1999a)

claimed that many areas throughout the Intermountain West were formerly savannas, and our sites conform to this classification, many areas were also piñon–juniper forests, which have not experienced change in tree densities and are not in need of restoration through thinning and burning (Romme et al., 2003). This emphasizes the importance of assessing site specific changes in stand structure and fire history for best restoration results. Understanding changes, if any, in presettlement forest structure, as well as landscape characteristics (topography, soils, etc.), can perhaps be an initial step in understanding the potential role and frequency of fire in piñon–juniper ecosystems and determining if fire is an appropriate tool to use in restoration (Romme et al., 2003).

We chose the date of 1860 for our reconstruction because it provides the best, latest evidence of piñon–juniper stands on a natural evolutionary trajectory. Our goal in reconstructing and restoring piñon–juniper ecosystems was not to reverse time, because clearly we live in a dynamic world that includes dramatic climate fluctuations. Our goal, rather, was to identify and understand a time period when healthier, more intact, functioning ecosystems dominated the Southwest landscape, a goal that is tangible and can be informed by ecological evidence. Using this time period to guide management and treatments should promote the 'health' of piñon–juniper ecosystems so they can better respond to current and pending environmental changes by maintaining plant and animal biodiversity and watershed resources.

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