Pinyon-Juniper Fire Regime: Natural Range of Variability

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Final Report

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EXECUTIVE SUMMARY

In this study, we used a variety of methods to quantify and describe historical patterns of fire and forest structure in two pinyon-juniper ecosystems of the Southwest. Sites were located on the Kaibab National Forest in Arizona, south of Grand Canyon National Park (Tusayan), and on the Carson National Forest in New Mexico, north of Espanola (Canjilon). Methodological approaches included analysis of fire scars, contemporary forest structure, fire evidence, modern fire records, and forest reconstruction. GIS surface maps, constructed using inverse distance weighted interpolation, were used to assess spatial patterns of fire and forest structure. Results indicated distinct fire histories and recent forest changes at the two sites. At Tusayan, surface fires burned historically at frequencies of 7.2-7.4 years (Weibull median probability) in canyons and draws dominated by ponderosa pine. On uplands dominated by pinyon-juniper communities, longer point fire intervals suggested fires occurred at a mean frequency of 41.6 years. Point intervals stratified by species indicated longer return periods for Utah juniper than pinyon or ponderosa pine. Fire evidence in the form of charred tree structures was ubiquitous at the site and there was no clear relationship between stand age and fire evidence. Live, old trees (>300 yr) were prevalent and averaged 26 trees per hectare (TPH). Stands were all ages up to 400 yr and patch sizes were generally small (<30 ha). Reconstructions showed a moderate overall increase (39%) in stand density since the late 19th century. Ponderosa pine increases were responsible for the majority of recent structural changes although pinyon density also had apparently increased. We found no evidence of extensive stand replacing fire over the last 400 years at Tusayan and concluded that the historical pattern has been one of frequent surface fires in ponderosa pine communities and small severe fires on pinyon-juniper uplands. At Canjilon, fire scar analysis showed longer mean fire intervals (81.1 yr), suggesting that infrequent crown fires or severe surface fires were an important component of the historical regime. Like Tusayan, charred structures were found across the Canjilon site, although they appeared to be more abundant at lower elevations where stands ages were younger. Few live old trees (>300 yr) were found at the site (4.2 TPH). The site dominated by stands in the 200-250-yr and 250-300-yr age classes. Mean patch sizes for stands of these age classes were 24 and 79 ha, respectively. Reconstructions showed relatively greater increases in tree density (61%) with Rocky Mountain juniper and pinyon pine both showing positive changes since the late 19th century. Evidence of stand replacing fire was seen along the eastern edge of the study site and young trees appeared to be encroaching into previously open areas, particularly around big sagebrush meadows. Woodland treatments that may parallel historical patterns of fire and forest structure at these sites include targeted tree thinning and/or use of prescribed fire to create canopy openings of various sizes.

INTRODUCTION

Pinyon-juniper woodlands cover approximately 22.5 million hectares in the western United States and are a dominant vegetation type on the semi-arid landscapes of the Southwest (Brown 1994, Powell et al. 1994). Pinyon-juniper woodlands typically occur at elevations of 1,500-2,500 m above sea level but are highly variable in species composition and structure (West et al. 1998). Overstories are commonly composed of Colorado pinyon pine (*Pinus edulis*) or singleleaf pinyon (*P. monophylla*), Utah juniper (*Juniperus osteosperma*), one-seed juniper (*J. monosperma*), alligator juniper (*J. deppeana*), and/or Rocky Mountain juniper (*J. scopulorum*) (Brown 1994). Stand structure ranges from open grass savanna to closed forest and is determined by disturbance history and physical site factors (Gottfried et al. 1995, West et al. 1998, Romme et al. 2003). Likewise, understory composition and structure are highly variable (West et al. 1998). Although these ecosystems are not considered important from a commercial timber production standpoint, they are valued for forage, fuelwood, wildlife habitat, watershed stabilization, recreation, aesthetics, and other woodland products (Gottfried et al. 1995). Recently, there has been renewed interest in formulating sound, science-based management strategies for pinyon-juniper woodlands (Gottfried and Severson 1994, Monsen and Stevens 1999, Romme et al. 2003). As public concern over wildfire danger increases, development of ecological approaches will be particularly important for pinyon-juniper lands in the wildland-urban interface. On these lands, human communities are perceived to be at risk and fuel hazard reduction programs are considered high priority. In order to conserve resource values in the wildland-urban interface, management strategies should be based on the best information available as related to long-term ecosystem patterns. Local studies are needed to describe historical ranges of variation in natural disturbance processes and structural variation (Romme et al. 2003, Landis and Bailey 2005). To date, very little is known about long-term disturbance regimes of these ecosystems.

Tree density has apparently increased on many pinyon-juniper sites in the Southwest and Great Basin (Tausch et al. 1981, Jacobs and Gatewood 1999, West 1999, Romme et al. 2003). It is difficult, however, to make generalizations concerning the causes of these increases. Changes in structural characteristics of other forest types in the western United States have been linked to fire exclusion, livestock grazing, and logging near the time of EuroAmerican settlement about 130 years ago (Bonnicksen and Stone 1982, Covington et al. 1994, Swetnam and Baisan 1996, Fulé et al. 1997, Baisan and Swetnam 1990, Mast et al. 1999, Moore et al. 2004). Before settlement, low intensity surface fires and herbaceous understory competition precluded abundant tree establishment and maintained open forest conditions in many ponderosa pine and mixed conifer ecosystems (Madany and West 1983, White 1985, Fulé et al. 1997, Mast et al. 1999, Moore et al. 1999). However, for pinyon-juniper ecosystems, few high quality data sets are available that describe historical ranges of variability of overstory structure or fire regime (West 1999, Baker and Shinneman 2004). Methods based on analysis of fire-scarred trees are problematic because pinyon tends to either burn completely, or not at all, and crossdating annual growth rings of juniper is very difficult (West 1999). Methodologies that combine information from fire-scarred trees with other lines of evidence, such as stand ages, charcoal, and historical fire maps, are needed to more clearly illustrate natural disturbance patterns in these ecosystems (Floyd et al. 2000).

Although uncertainty exists, it appears that frequent surface fires in pinyon-juniper most likely occurred on highly productive sites with finely textured soils that could support extensive fine fuel complexes (Gottfried et al. 1995, Swetnam and Baisan 1996, Gruell 1999, Romme et al. 2003). Fire-maintained pinyon-juniper savannas may have occurred on sites in Arizona, New Mexico, and Mexico (Jameson 1962, Dwyer and Pieper 1967, Segura and Snook 1992, Landis and Bailey 2005). On these sites, recent increases in tree density may represent anthropogenic changes brought about by livestock grazing and fire exclusion. Lower frequency, mixed regimes or stand replacing fires were probably common on less productive sites with rocky soils or where topographic influences broke fuel continuity, (Tausch and West 1988, Gruell 1999, Floyd et al. 2000, Romme et al. 2003). Closed old-growth forests are present on various sites in Arizona, Colorado, Nevada and Utah (Tausch et al. 1981, Kruse and Perry 1995, Floyd et al. 2000, Rowlands and Brian 2001). On these sites, recent increases in tree density may represent natural successional processes (Romme et al. 2003).

In dense forests, mechanical tree thinning and reintroduction of surface fire are being widely used in fuel hazard reduction programs. In historically open forests where frequent fire was a critical ecosystem process, thinning and prescribed fire also are important components of ecological restoration prescriptions (Covington et al. 1997, Jacobs and Gatewood 1999, Moore et al. 1999, Allen et al. 2002, Fulé et al. 2002, Waltz et al. 2003). Ecosystem restoration relies on halting processes of degradation and formulating strategies to help return conditions to near their natural ranges of historic variability (SER 2002). Although reference conditions appear to be highly variable and site specific in pinyon-juniper ecosystems, Romme et al. (2003) and Baker and Shinneman (2004) have expressed concern that fuel reduction prescriptions may be justified under inappropriate "ecological restoration" assumptions. Identifying the natural range of variability in disturbance patterns and ecosystem structure is therefore critical in determining the need for ecological restoration for specific sites. In this study, our goal was to increase understanding of historical variability in pinyon-juniper fire regimes of the Southwest. We used multiple methodological approaches to fully investigate historical patterns of fire and stand structure at two sites of similar soils, climate, and vegetation.

OBJECTIVES

The specific objectives of this study were to do the following:

1. Describe fire history and historical disturbance patterns in pinyon-juniper ecosystems of northern Arizona and New Mexico using a variety of methodologies, including analysis of basal fire scars, stand age structure, and historical fire maps.
2. Interpret fire regime data in terms of the range of natural variability of these ecosystems, drawing implications for conservation, hazardous fuel treatment, and ecological restoration.
3. Carry out a survey of pinyon-juniper ecosystems in Arizona and New Mexico, categorize and prioritize future study sites, and initiate sampling on one New Mexican site.

METHODS

Study Sites

Fire history and reference conditions studies were conducted at two southwestern pinyon-juniper sites. We intentionally located sites of similar soils, climate, and vegetation in distinct geographical areas in the Southwest. One site was selected on the Tusayan Ranger District of the Kaibab National Forest (hereafter, "Tusayan"). To find a second site, we used terrestrial ecosystem survey (TES) descriptions and considered various locations in northern New Mexico. We selected a second site on the Canjilon Ranger District on the Carson National Forest in New Mexico (hereafter "Canjilon") (Fig. 1). The Tusayan site was located immediately south of Grand Canyon National Park and comprised approximately 770 hectares. The Canjilon site was approximately 61 km northwest of Espanola, NM on La Mesa de Las Viejas and was 409 hectares in size.

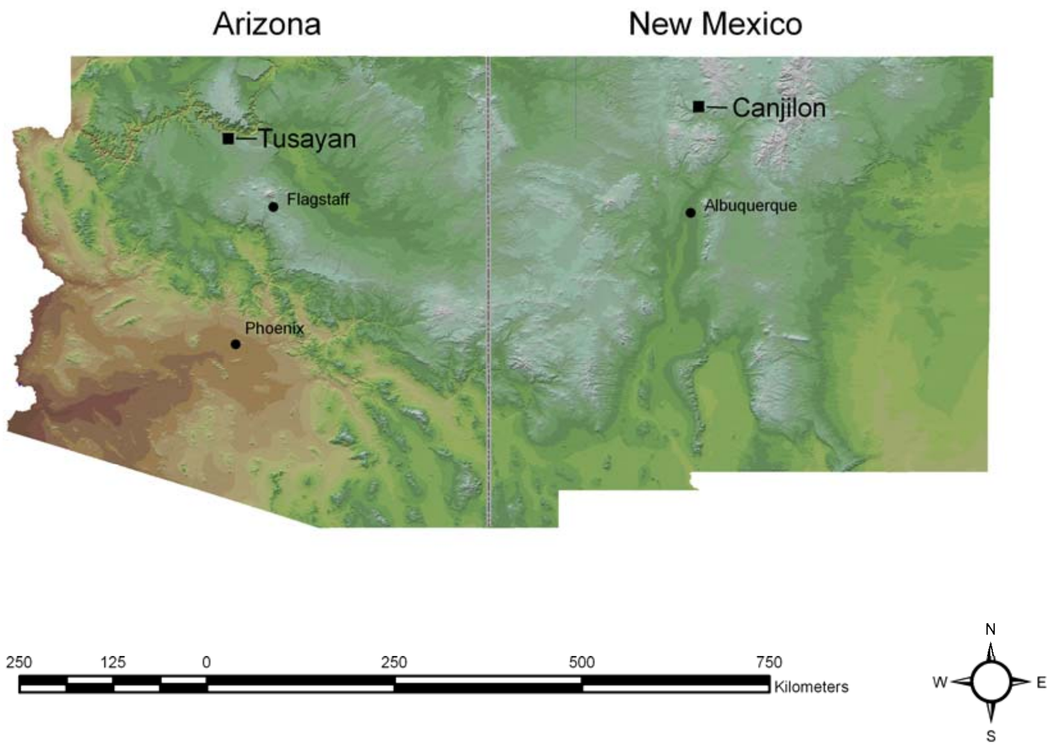

Figure 1. Location of Tusayan and Canjilon study sites in Arizona and New Mexico.

Tusayan

The Tusayan site was located within an ecotonal zone and included ponderosa pine (*Pinus ponderosa*) forest and pinyon-juniper woodland communities. Elevation at the site ranged from 2,005 meters to 2,073 meters above mean sea level. Topography could be described as relatively flat uplands dissected by shallow canyon draws. Annual precipitation averaged 430 mm, falling mainly July-March (Western Regional Climate Center 2006). Average maximum and minimum temperatures were 17 and 0º C, respectively. Soils at the site were mainly typic eutroboralfs, lithic haploborolls, and typic haplustalfs formed in residuum from limestone and sandstone parent material (USDA Forest Service 1991). The site represented TES map units 261, 272, 275, and 283 (USDA Forest Service 1991). Pinyon-juniper woodlands were present on the upland microsites (approx. 80% of the total area) and ponderosa pine forests occupied the canyon draws (approx. 20% of the area). Pinyon-juniper vegetation at the site was classified as Great Basin Conifer Woodland (Brown 1994). Overstory tree species were primarily pinyon pine (*Pinus edulis*,) Utah juniper (*Juniperus osteosperma*), ponderosa pine, and Gambel oak (*Quercus gambelii*). Understory communities were comprised of shrubs such as cliffrose (*Purshia mexicana*), big sagebrush (*Artemisia tridentata*), and Apache plume (*Fallugia paradoxa*); grasses such as blue grama (*Bouteloua gracilis*) and muhlenbergia (*Muhlenbergia* spp.); and forbs such as buckwheat (*Eriogonum* spp.) and gilia (*Ipomopsis* spp.).

Resource use and management activities at the Tusayan site over the last 130 years have varied in intensity. We assumed that the site was intensively grazed by domestic livestock in the late 1800s and early 1900s (Miller 1921, Anderson 1998, Olberding et al. 2005). No livestock grazing has occurred on the site since 1996, although severe overstocking had been noted for several decades prior to this time (D. Brewer, US Forest Service, personal communication). Ponderosa pine stumps and old log decks observed at the site suggest a significant timber harvest that may have occurred around 1930 when logging railroads reached the area (Putt 1995). Recently, the site experienced minor fuelwood harvesting of dead and down pinyon and juniper trees. A limited number of small wildfires have occurred in the last 35 years (see Results) and a prescribed fire was implemented across nearly half the site in 1993.

Canjilon

Similar to the Tusayan site, the Canjilon site was within a transitional zone between ponderosa pine forests and pinyon-juniper woodlands. Elevation at the site ranged from 2,347 m to 2,438 m above sea level with the eastern study site boundary at the abrupt edge of La Mesa de Las Viejas. Annual precipitation averaged about 388 mm with a pronounced peak of occurrence July-September (Western Regional Climate Center 2006). Average maximum and minimum temperatures were 17 and -2.7º C, respectively. Soils at the site were mainly typic ustochreptss, typic eutroboralfs, and typic haplustalfs derived from various parent material sources including shale (USDA Forest Service 1987). Vegetation of the area was described as Southern Rocky Mountains (RM-2), Mountain Loam, Mountain Slope, and Mountain Shale (NRCS 2006). The site represented TES map units 119, 157, and 162 (USDA Forest Service 1987). Overstory tree composition was dominated by pinyon pine (*Pinus edulis*) and Rocky Mountain juniper (*Juniperus scopulorum*) interspersed with stands of ponderosa pine (*Pinus ponderosa)* and Gambel oak (*Quercus gambelii*). Understory communities were comprised of shrubs such as big sagebrush (*Artemisia tridentata*), mountain mahogany (*Cercocarpus montanus*), and rabbitbrush (*Ericameria nauseosa*); grasses such as blue grama (*Bouteloua gracilis*) and mutton grass (*Poa fendleriana*); and forbs such as buckwheat (*Eriogonum* sp.) and hymenoxys (*Hymenoxys* sp.). Historical land use at the Canjilon site is not well known, although Native American and Hispanic activities are likely to have influenced woodland structure and dynamics to some extent before the late 19th century. More recently (ca 1951), efforts were made to rehabilitate overgrazed land on La Mesa de Las Viejas (Scurlock 1998).

Field Sampling

Fire Scars

Partial cross sections of fire-scarred tree structures were collected in order to examine patterns of historical, low-severity fire. At both research sites, we made use of the fire evidence (i.e., charred tree structures) transects described below to search for fire-scarred trees. Spatial location of scarred trees, species, diameter, condition, and number of apparent fire scars were recorded for each scarred tree found along transects. These data helped us to target samples for fire scar collection. In addition, areas at the Tusayan site with an apparent high density of fire-scarred trees but not sampled by transects were thoroughly searched. Samples of fire scars were collected for fire history analysis by removing a partial cross-section of the tree structure with a chainsaw following methods described by Arno and Sneck (1977). For each scar collected, data regarding spatial location, slope and aspect of the microsite, species, condition, location of the scar, and number of visible scars were recorded. Samples were brought back to the laboratory where they were mounted on plywood backing, sanded, and analyzed under a binocular microscope. At Tusayan and Canjilon, 120 and 66 samples were collected, respectively.

Woodland Structure

In order to examine woodland structural characteristics that may indicate past disturbance patterns, we systematically established sample plots on 200-m x 200-m grids at both sites (Fig. 2). Sample plots were circular and 0.04 ha (11.28 m radius) in size. At the Tusayan site, 182 plots were established across the site and at Canjilon 106 plots were established. Sampling was conducted June-August 2004 at the Tusayan study site and June-July 2005 at Canjilon. Overstory trees, tree regeneration, and woody understory plants were measured on each sample plot at the two sites. Within each plot, all trees were identified to species and condition class was recorded following a classification system commonly used in ponderosa pine forests (Maser et al. 1979, Thomas et al. 1979). The nine classes were: 1) live, 2) fading, 3) recently dead, 4) loose bark snag, 5) clean snag, 6) snag broken above breast height, 7) snag broken below breast height, 8) dead and down, and 9) cut stump. All pinyon and juniper trees were measured for diameter at root collar (DRC; measured at ground level). For multiple-stemmed pinyon and juniper trees, DRC was recorded for each stem. Live ponderosa pine and Gambel oak trees were measured for diameter at breast height (DBH; measured at 1.37 m above ground) whereas dead trees of these species were measured at 40 cm above root collar (DSH). Gambel oak (*Quercus gambelii*) trees smaller than 10.0 cm DBH were tallied. Live and standing dead trees were measured for height. At both sites, increment cores were collected at DSH to determine age of live trees. At the Tusayan site, increment cores were collected from all pinyon and juniper trees greater than 25 cm DRC and ponderosa pine greater than 37.5 cm. Additionally, a random 20% of trees with smaller diameters were sampled for age. Tree age sampling at the Tusayan site was conducted on 48 randomly selected plots. At Canjilon, increment cores were collected from a 20% sample of all live trees across all plots. For dead and down trees at both sites, log decomposition class (LDC; Sollins 1982) was recorded. Any presence of char or fire scars on all trees was recorded. Shrubs and tree seedlings (<1.37 m in height) were tallied by species and condition class on smaller, nested plots (0.01 ha). These data allowed us to determine stand ages and composition as well as reconstruct historical woodland characteristics (see Analysis: Stand Reconstruction).

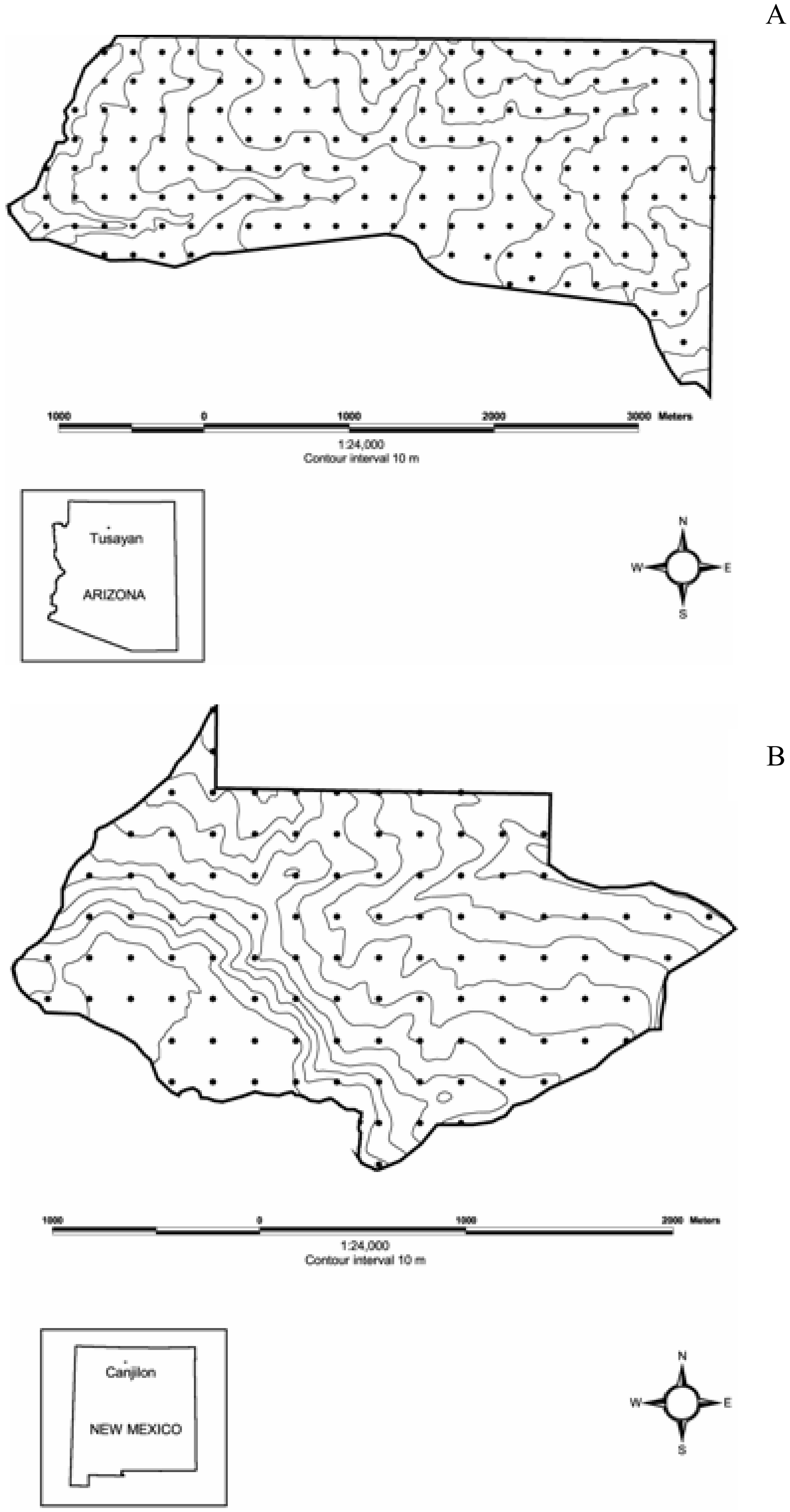

Figure 2. Tusayan (A) and Canjilon (B) study sites, showing sample plots on 200-m grid.

Charred Tree Structures

In order to identify areas of recent fire and those that may have experienced stand replacing fire, we searched both research sites for charred tree structures. At each site, 100-m wide transects running the entire length of the study area were used to inventory charred tree structures. At the Tusayan site, 50% of the total area was surveyed and spatial coordinates, species, diameter (following above description), condition, and LDC (dead and down) were recorded for each charred structure found. In 1993, a prescribed burn was conducted over approximately one-third of the site and resulted in a high concentration of charred trees. In this area, we established a 0.25-ha plot at 2-4 random points along each transect in order to determine charred structure density. At the Canjilon site, we conducted a complete census of charred trees using transects as described above.

Fire Records

Fire records were collected from US Forest Service archives in order to describe characteristics of modern fires. Records available were in both electronic (geographical information system) and paper form and included the following data: fire location, date, size class, cause, and name. For Tusayan, records from as early as ca 1950 were available. Records as early as ca 1970 were available for Canjilon. These data served as points of reference for assessing effects on woodland structure and interpreting other evidence such as charred trees and fire scars.

Analysis

Fire Scar Analysis

Historical fire frequency was assessed by analyzing scars discernable on partial cross-sections collected at the two field sites. Samples from fire-scarred trees were crossdated using local master chronologies (Stokes and Smiley 1996) and accuracy of crossdating was verified using the computer software COFECHA (Grissino-Mayer 2001). Date and season of fire occurrence was estimated based on the relative position of fire lesions within each annual ring (Baisan and Swetnam 1990). Fire return intervals were calculated using FHX2 software (Grissino-Mayer 1995). Fire return intervals were determined for the set of all scars as well as for only the fire dates that occurred on 10% or more of the samples. The 10% filter corresponds to increasing size and/or intensity of fires, removing the fire dates represented by only one or a few samples (Swetnam and Baisan 1996, Baker and Ehle 2001). We did not use any specific criteria to determine a date from which to begin the analysis; rather, we included the earliest fire date observed on our samples. Descriptive statistics of mean fire interval (MFI) and Weibull median probability interval (WMPI) were generated. In addition, point mean fire intervals (PMFI) were calculated for individual samples showing two or more fire scars.

Woodland Structure

Overstory species importance values were calculated as the relative proportion of plot TPH + the relative proportion of plot BA for each overstory species (Taylor and Skinner 1998). Thus, complete dominance of a species would result in an importance value of 200 (i.e., 100% TPH + 100% BA).

Shrub density was calculated for each plot by summing tallies of shrub individuals. An index of relative shrub density was defined by stratifying tallies into three classes: 1) 0-2,500; 2) 2,500-10,000; and 3) >10,000 individuals per hectare. Species frequency was calculated as the number of plots on which a species occurred divided by the total number of sample plots across the study site. Oak density and conifer regeneration (stems per hectare; TPH) was calculated for each plot by combining size class tallies for live individuals.

We used tree increment cores to develop tree diameter-age relationships. Relationships were analyzed with simple linear regression (alpha = 0.05) (Figs. 3 and 4). Predictive equations were used to estimate age for all trees for which no increment cores were collected. No *J. osteosperma* cores were collected at the Canjilon site so for this species we used the age-size relationship developed for *J. scopulorum*. Stands ages were assigned based on the maximum age of pinyon trees in each plot. Pinyon age was used since sample size was greatest for this species, it was generally distributed across the study sites, and dendrochronological crossdating of increment cores was possible. Using pinyon age on plots, we created stand maps to assess structural patterns that may have arisen from historical wildfires (see ***GIS Analysis*** below).

Stand Reconstructions

Overstory tree density (TPH) by species was reconstructed on each plot in order to estimate conditions existing prior to EuroAmerican settlement (hereafter "presettlement") of the areas. Hispanic settlement of the Chama valley, south of the Canjilon site, began in the 1740s but the widespread effects of changes in land management practices, notably livestock grazing that reduced fuels for fire spread, were nearly contemporaneous in the late 19^{th} century in both New Mexico and Arizona. The dates of 1887 and 1890 were selected for Tusayan and Canjilon reconstructions, respectively. These dates represent the interruption of natural fire regimes in ponderosa pine forests near the sites and thus may have been points of substantial departure from historical ranges of structural variability (Swetnam and Dieterich 1985, Touchan et al. 1996, Fulé et al. 2002). Size-age relationships described above were used to estimate a presettlement size. Trees greater than or equal to this size were considered presettlement in origin and included in reconstruction estimates. For example, pinyon trees ≥ 12.7 cm DRC at the Tusayan site were predicted to be 117 years old (2004-1887 = 117) or greater and included in the reconstruction estimate (refer Fig. 3). Once dead, pinyon trees can decompose and become highly fragmented within 25 years or less (Kearns et al. 2005). For this reason, all dead pinyon and ponderosa pine trees were included in reconstruction estimates if found to be greater than or equal to the estimated presettlement size. In contrast, juniper trees decompose relatively slowly (Landram et al. 2002) and therefore highly decomposed junipers (LDC > 3) were assumed to be dead prior to the reconstruction dates and not included in estimates. Reconstructed conditions were summarized by plot. Paired t-tests were used to test whether mean tree densities differed ($P < 0.05$) between reconstructed and contemporary periods. We also used increment core data and size-age relationships to evaluate density of live "old" trees (≥ 300 yr).

GIS Analysis

In order to examine spatial patterns of woodland structure and fire evidence, surface maps were constructed using inverse distance weighted (IDW) interpolation of overstory and understory plot data in ArcView GIS Spatial Analyst (McCoy and Johnston 2001). This technique allowed grid cell values to be estimated from sample points within the vicinity. Because our sample plots were 0.04 ha in size and spaced on a regular 200-m grid across the study sites, we used a 20-m cell size and 250-m fixed radius cell neighborhood. Variables interpolated were overstory species importance, relative shrub density, density of Gambel oak, conifer regeneration, contemporary and reconstructed tree density, density of live old trees, and maximum pinyon age. Cells of interpolated surfaces were reclassified into logical divisions and these maps were analyzed using the FRAGSTATS extension designed for raster GIS coverages (McGarigal and Marks 1995). Landscape metrics evaluated for each variable were total class

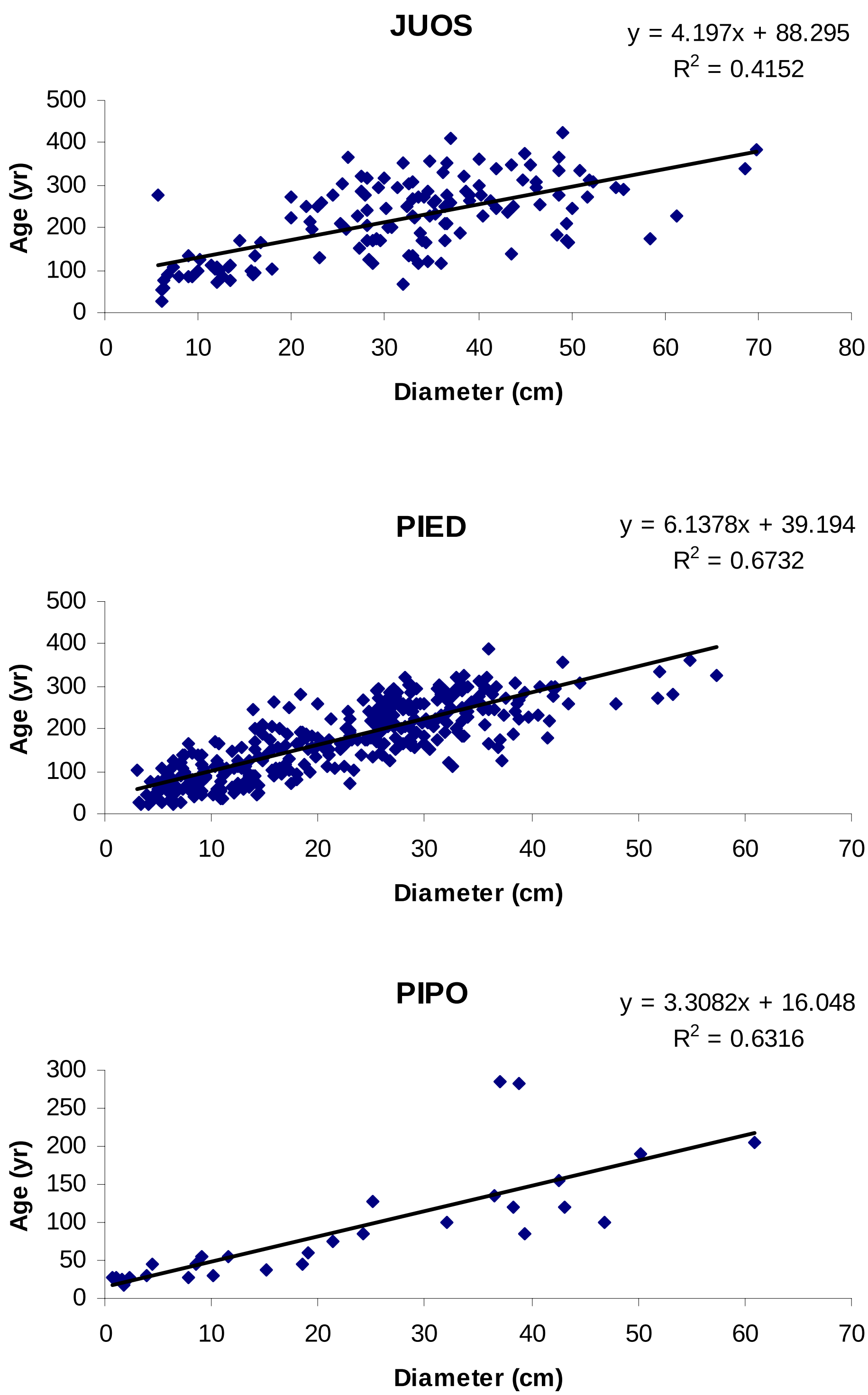

Figure 3. Age-diameter relationships used to predict tree ages for pinyon pine (PIED), Utah juniper (JUOS), and ponderosa pine (PIPO) trees at the Tusayan study site.

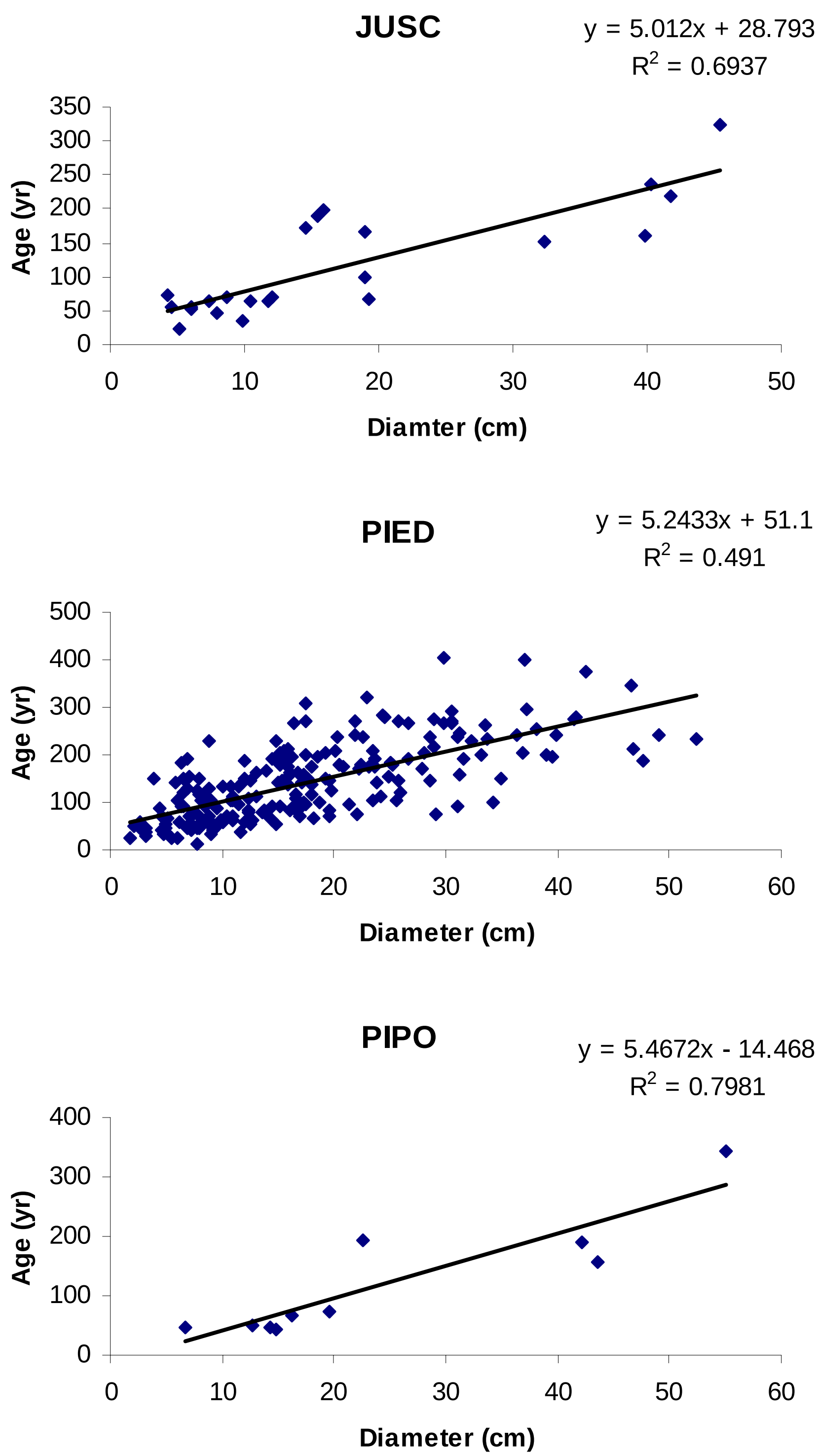

Figure 4. Age-diameter relationships used to predict tree ages for pinyon pine (PIED), Rocky Mountain juniper (JUSC), and ponderosa pine (PIPO) trees at the Canjilon study site.

area, number of patches per class, and mean patch size. Additionally, locations of fire charred tree structures and partial cross-section samples were overlaid on surface maps of maximum pinyon age in order to evaluate patterns that may have developed as a result of historical fires.

RESULTS

Historical Fire Frequency

Tusayan

A total of 120 partial cross-sections was collected from the tree structures at the Tusayan study site. Sample intensity by species reflected the relative availability of fire scars at the site. Of the collected samples, 80% were taken from ponderosa pine tree structures, about 43% from cut ponderosa pine stumps (Table 1). Fifteen percent of the scars were collected from pinyon pines whereas only 5% were taken from junipers. Of the 120 collected samples, we were able to successfully crossdate 43. Eighty-five percent of the dated samples were ponderosa pine and the remainder was pinyon; we were not able to crossdate juniper (*J. osteosperma*) samples at the Tusayan site. On crossdated samples, a total of 109 fire scars was observed. Of these scars, we were able to confidently assign dates to 75; dates of the remaining fire scars were considered "uncertain" fire dates. Based on crossdated scars, the period with the highest number of recorded fires prior to 1887 was the early 1600s with 12 fire years observed in the first half-century and 4 fire years in the latter half-century. Only two fire years were determined for the 1700s whereas 14 fire years were found in the 1800s. Twenty-one percent of all fire years recorded occurred after 1900; twelve fires were recoded for the period 1887-2004 and five samples recorded the 1993 prescribed fire. For all crossdated fire scars, historical (pre-1887) MFI was 10.9 years and WMPI was 7.2 years (Fig. 5). For larger fires – those that were recorded on 10% or more of the samples – MFI was 11.6 years and WMPI was 7.4 years. Fire scar dates indicated that widespread fires occurred throughout the 1600s and 1800s

Sample mean intervals from individual trees that showed more than one fire scar (n = 20). These intervals include ring counts on pinyon and juniper trees as well as crossdated scars (Fig. 6). Analysis of individual sample intervals indicated that fire intervals on ponderosa and pinyon pine trees were less than 82 years prior to 1887; 75% of these intervals were 42 years or less. For juniper trees with more than one scar (n = 4), mean sample interval ranged from 35 to 111 years (PMFI for all species combined = 41.6 yr; SD = 31.7).

Canjilon

At the Canjilon study site, 61 partial cross-sections were collected. Of these, 38% were from ponderosa pine and an equal amount was collected from pinyon pine (Table 1). Twenty-three percent were from juniper (*J. scopulorum*) and one scar was collected from a Gambel oak. A total of 24 samples were crossdated and on these 74 fire scars were observed. Of these scars, we were able to confidently assign dates to 31. These scars indicated that, similar to findings at the Tusayan site, the 1600s showed the greatest number of fires (n = 6 fire years) prior to EuroAmerican settlement (1890 for Canjilon). Five fire years were determined for the 1700s and 3 fire years were identified for the 1800s. One-third of the fire years occurred in the 1900s and eight fires were recorded for the period 1890-2005. For all crossdated scars as well as those scarring 10% or more of the recording samples at the Canjilon site, pre-1890 MFI was 22.5 and WMPI was 11.1 (Fig. 7). For individual samples four out of seven ponderosa pine samples had mean scar intervals ≤ 45 years (Fig. 8). Two of three pinyon pine samples showed interval means ≤ 45 years. In contrast, three of five juniper (*J. scopulorum*) samples had mean fire scar intervals ≥ 100 years (PMFI all species = 81.0 yr; SD = 58.3).

Table 1. Description of fire scar samples collected at the Tusayan and Canjilon study sites. Numbers in parentheses represent crossdated samples.

			Dead			
Site	Species[1]	Living	Standing	Down	Stump	*Total*
Tusayan	Juos	2 (0)	4 (0)	0 (0)	0 (0)	*6 (0)*
	Pied	7 (3)	2 (0)	8 (3)	1 (0)	*18 (6)*
	Pipo	21 (12)	7 (4)	16 (2)	52 (19)	*96 (37)*
	Total	*30 (15)*	*13 (4)*	*24 (5)*	*53 (19)*	*120 (43)*
Canjilon	Jusc	9 (0)	2 (0)	0 (0)	3 (1)	*14 (1)*
	Pied	13 (4)	4 (2)	1 (0)	5 (3)	*23 (9)*
	Pipo	10 (7)	5 (2)	0 (0)	8 (5)	*23 (14)*
	Quga	0 (0)	1 (0)	0 (0)	0 (0)	*1 (0)*
	Total	*32 (11)*	*12 (4)*	*1 (0)*	*16 (9)*	*61 (24)*

[1] Species codes: Juos: *Juniperus osteosperma*; Pied: *Pinus edulis*; Pipo: *Pinus ponderosa*; Jusc: *J. scopulorum*; Quga: *Quercus gambelii*

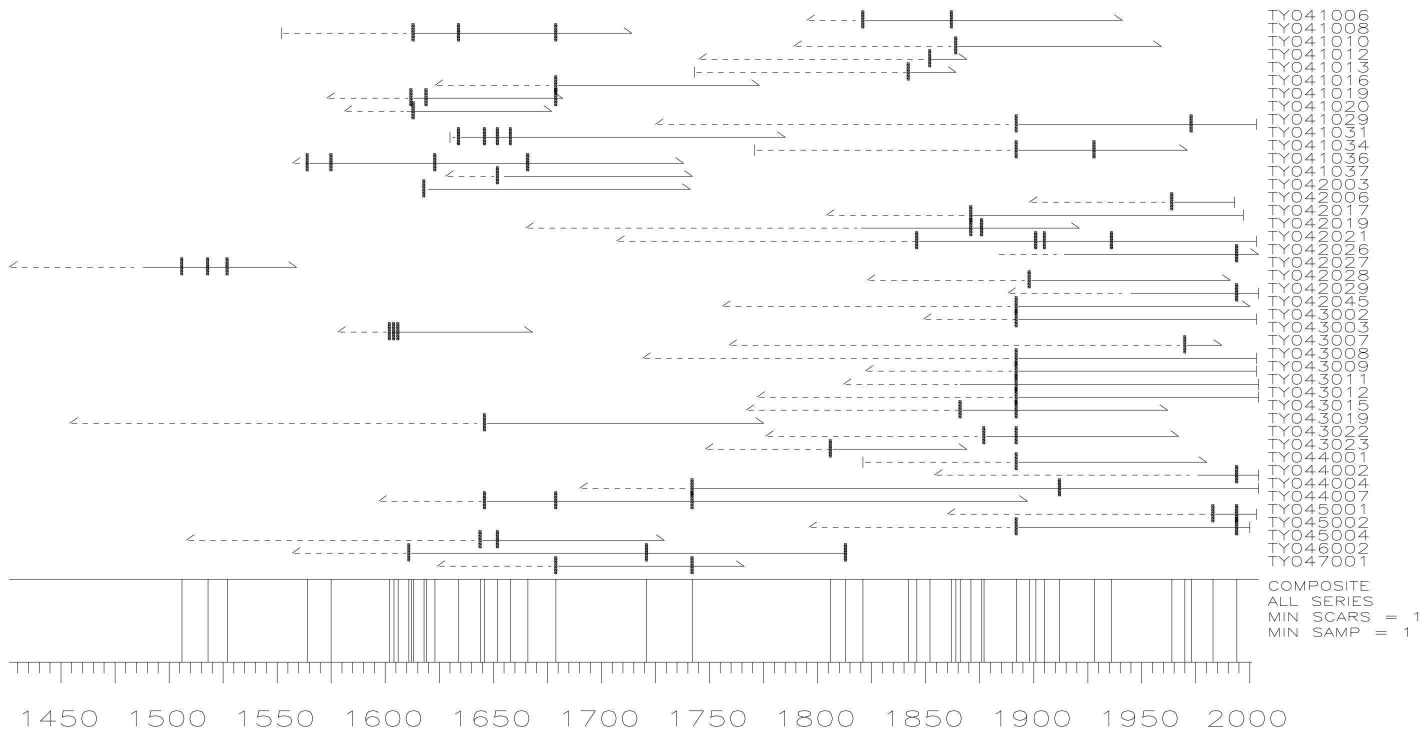

Figure 5. Composite fire history graph showing years for which fire scars (vertical lines) were found on all partial cross sections (n= 43; horizontal lines) collected at the Tusayan site. Mean fire interval for all scarred samples was 10.9 years whereas Weibull median probability interval (WFPI) was 7.2 years (MFI = 11.6 years and WMPI = 7.4 years ≥ 10% of the sample trees scarred).

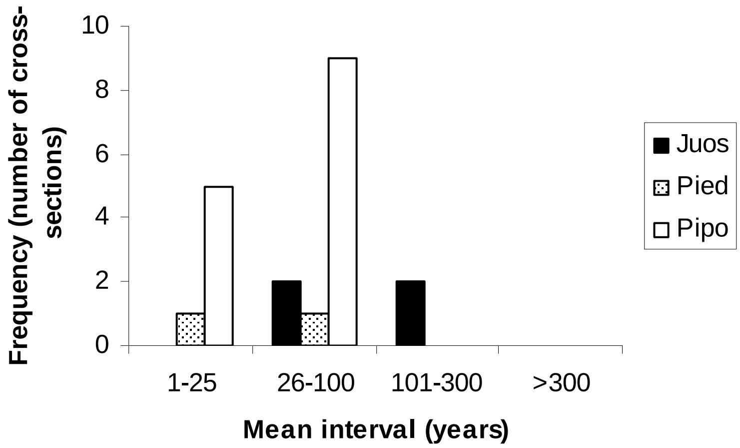

Figure 6. Distribution of point fire intervals for tree cross-sections collected at the Tusayan study site. Sample means of 1-25, 26-100, 101-300, and >300 represent fire regimes characterized as frequent-low severity, moderate frequency-moderate severity, low frequency-moderate to high severity, and low frequency-high severity, respectively. Figure shows mean intervals for Utah juniper (Juos), pinyon pine (Pied), and ponderosa pine (Pipo).

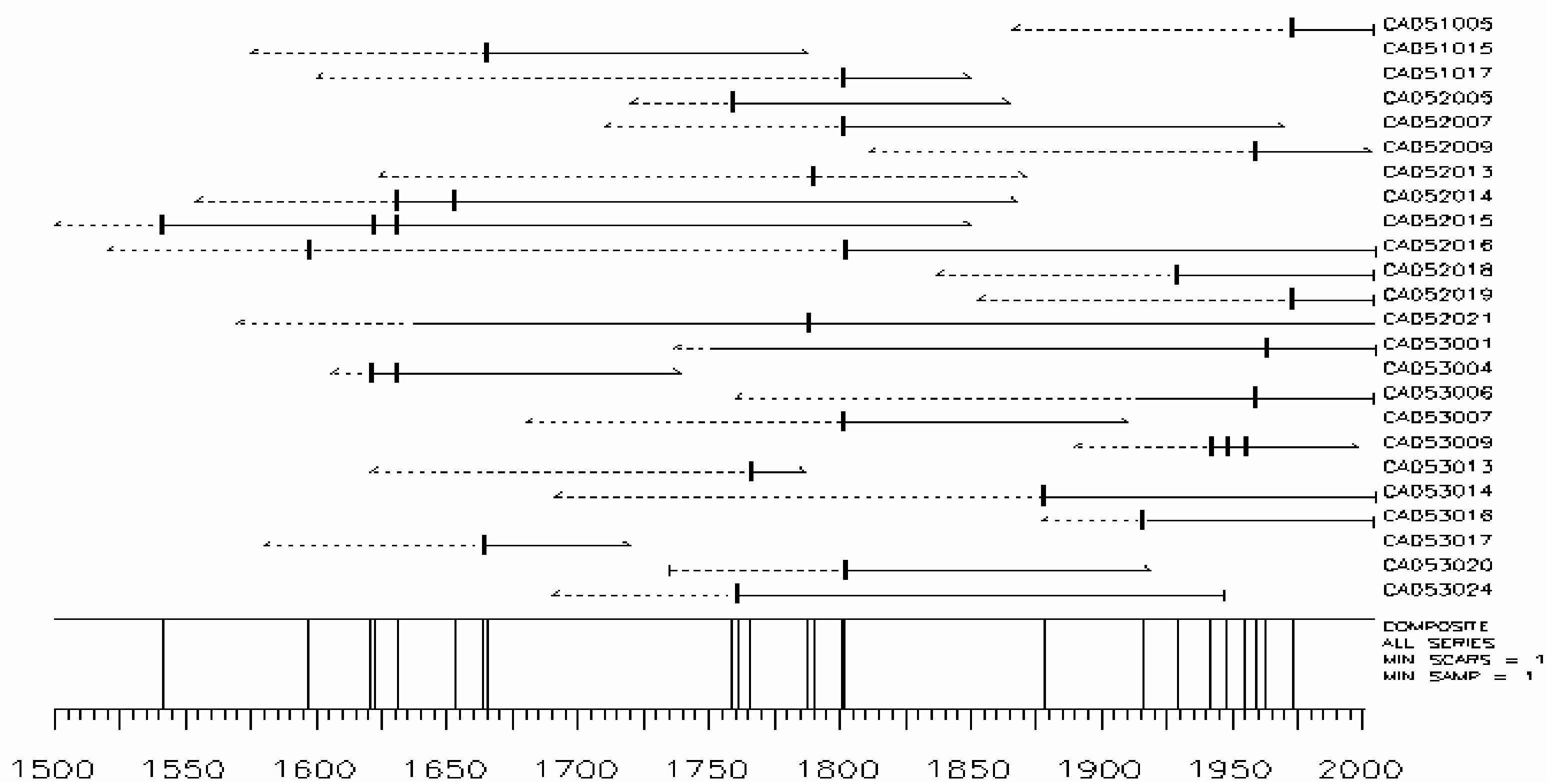

Figure 7. Composite fire history graph showing years for which fire scars (vertical lines) were found on all partial cross sections (n= 24; horizontal lines) collected at the Canjilon site. Mean fire interval for all scarred samples was 22.5 years whereas Weibull median probability interval (WFPI) was 11.1 years (MFI = 22.5 years and WMPI = 11.1 years ≥ 10% of the sample trees scarred).

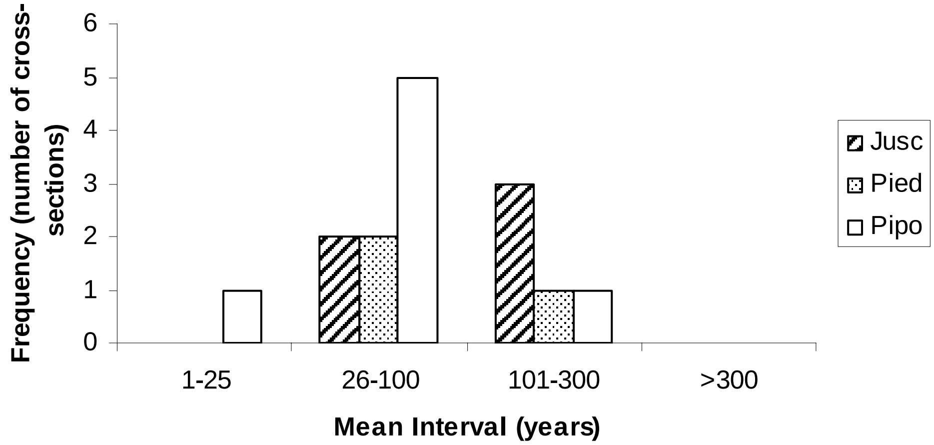

Figure 8. Distribution of point fire intervals for tree cross-sections collected at the Canjilon study site. Figure shows sample means for Rocky Mountain juniper (Jusc), pinyon pine (Pied), and ponderosa pine (Pipo).

Overstory Structural Conditions

Tusayan

Tree densities on sample plots at the Tusayan site ranged between 99 and 2,569 TPH, with a mean of 850 (SD = 414) TPH. Pinyon pine was the most numerous overstory species across the site with an average density of about 502 TPH. In contrast, ponderosa pine was the least abundant with a mean density of 120 TPH (Table 2). Tree density was variable across the site with denser patches found outside the area burned in 1993 by prescribed fire (Fig. 9). Patches in the prescribed burn area were generally 500-1,000 TPH, whereas outside the burn approximately half of the area showed patches of 1,000-1,500 TPH or greater. Density of live old trees (> 300 yr) ranged from 0 to 100 TPH, with a mean of 26 TPH (SD = 25). Patches of old trees appeared to be distributed irregularly across the study site and several dense patches occurred (50-100 TPH) within the area of the 1993 prescribed fire (Fig. 10).

The frequency of pinyon and juniper trees across the Tusayan study plots was 94-95%. Ponderosa pine trees occurred on 58% of the sample plots. Pinyon trees were the most dominant of the three main overstory species across the site (Fig. 11). Forty-seven percent of the study site area was comprised of patches with pinyon importance values of 100-150 (complete dominance = 200). In contrast, juniper was less important across the site, occurring at importance values of 50-100 on 70% of the area. Ponderosa pine trees were generally restricted to canyon and draw microsites but in these areas it occurred at high importance values (Fig. 11). Pinyon importance values were generally higher in ponderosa pine-dominated areas than were juniper, suggesting species segregation based on microsite conditions. It should be noted that we found the majority of our fire scar samples in areas of high ponderosa pine importance (see above).

Reconstructed (1887) tree density on sample plots ranged from 0 to 1400 TPH with a mean of 614 TPH (SD = 356), which was significantly fewer trees than 2004 conditions (Table 2). Increases in pinyon and ponderosa pine densities were 72% and 347%, respectively, whereas juniper density decreased by 47% over the period from 1887 to 2004. In the prescribed burn area, tree densities and patch locations did not appear to be substantially different than contemporary conditions (Fig. 9). In contrast, dense patches (1,000-1,500 TPH) occurred on about 25% of the area outside the burn; the majority of this area was comprised of patches with densities of 500-1,000 and 100-500 TPH.

Canjilon

Tree densities at the Canjilon site ranged from 0 (seven sample plots were located in shrub meadows) to 2,000 TPH with a mean of 771 TPH (SD = 423.3). The lowest density found on forested plots was 50 TPH. Similar to the Tusayan site, pinyon pine was the most numerous overstory tree found at Canjilon with a mean density of 621 TPH (Table 3). Rocky Mountain juniper (106 TPH) was present at about one-sixth the density of pinyon pine but was nonetheless the second most numerous species at the study site. Ponderosa pine density averaged about 36 TPH and Utah juniper was least abundant at the site averaging about 8 TPH (Table 3). The majority (67%) of the site was comprised of patches of 500-1,000 TPH (Fig. 12). Twenty-four percent of the landscape was made up of patches denser than 1,000 TPH and 9% of the landscape was in more open patches of less than 500 TPH. Live old trees (>300 yr) were relatively sparse across the study site and 82% of the landscape had 10 TPH or fewer (Fig. 13). Mean density of old trees at the site was 4.2 TPH.

Table 2. Mean number of trees per hectare (and standard error) by overstory species at the Tusayan site in 1887 and 2004. P-values ≤ 0.05 indicate statistically significant means between the two time periods.

Species	1887	2004	t	P
Juos	328.2 (15.8)	228.3 (10.9)	7.89	<0.001
Pied	292.3 (13.4)	501.7 (25.1)	9.96	<0.001
Pipo	26.9 (3.4)	120.3 (14.2)	7.33	<0.001
Total	*614.4 (26.2)*	*850.3 (30.5)*	*9.69*	*<0.001*

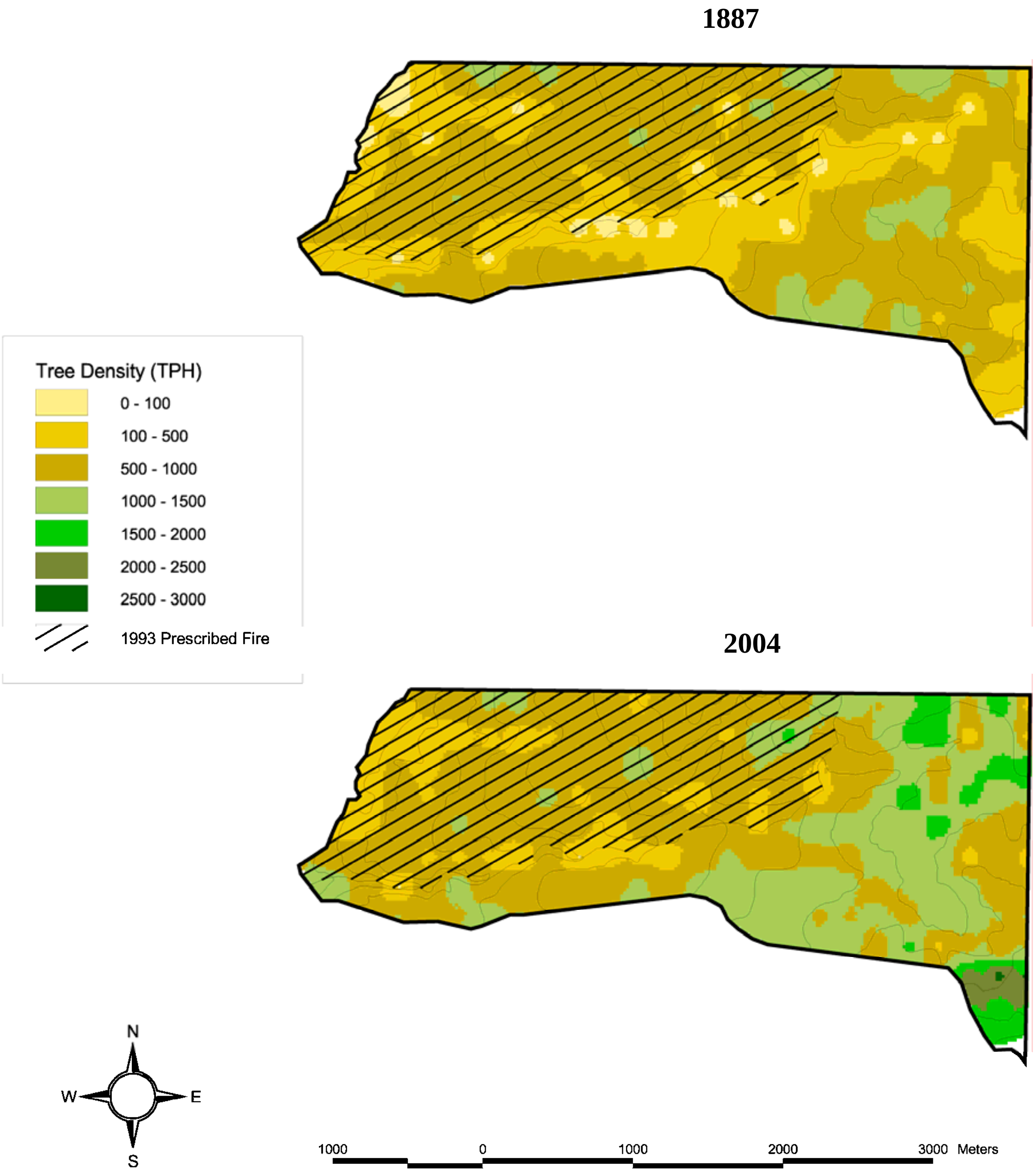

Figure 9. Map of reconstructed (1887) and contemporary (2004) tree density (TPH) at the Tusayan site. Crosshatching indicates area of 1993 prescribed fire.

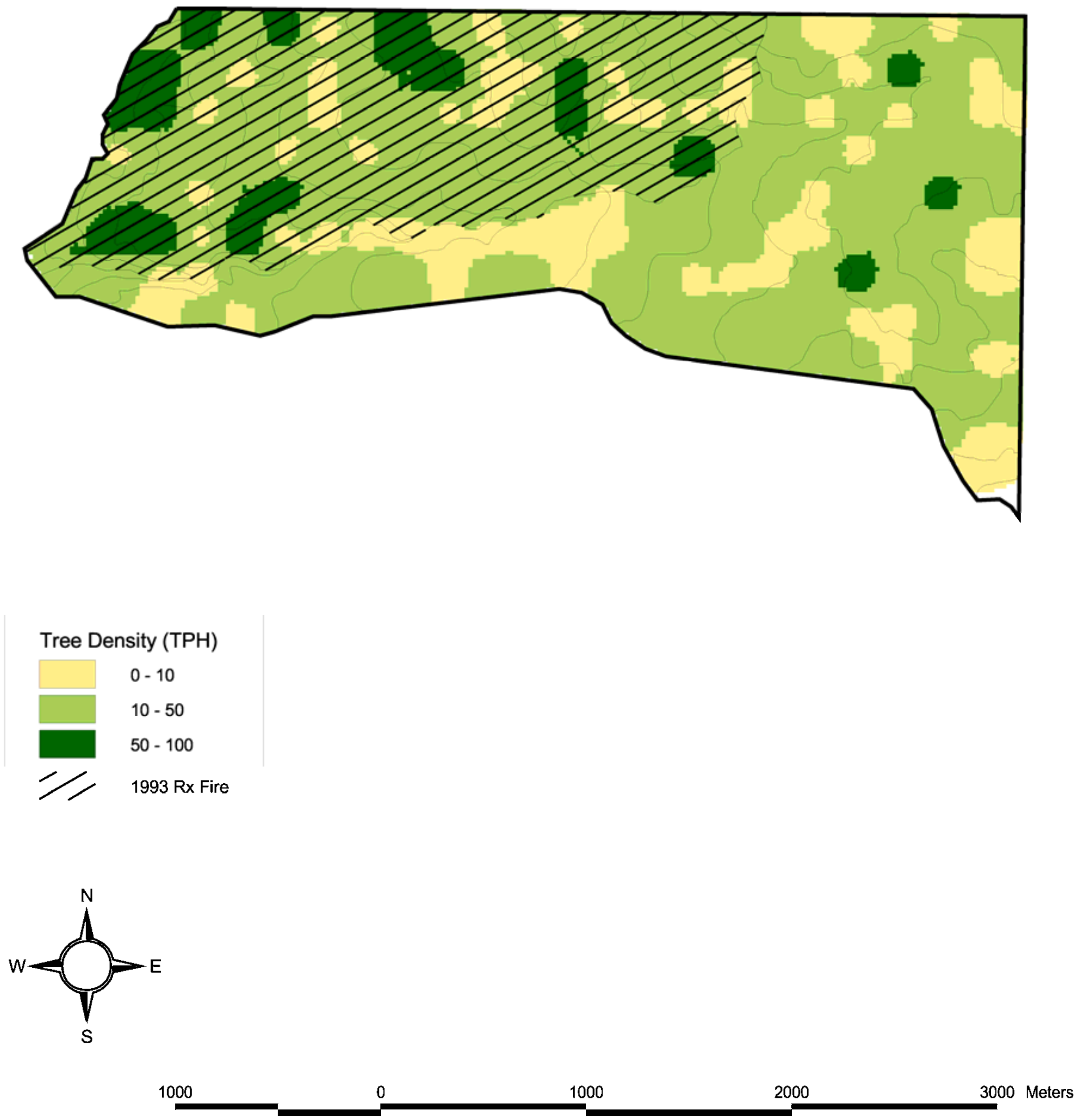

Figure 10. Map of density (TPH) of live, “old” trees (≥ 300 years of age) at the Tusayan site in 2004. Crosshatching indicates area of 1993 prescribed fire.

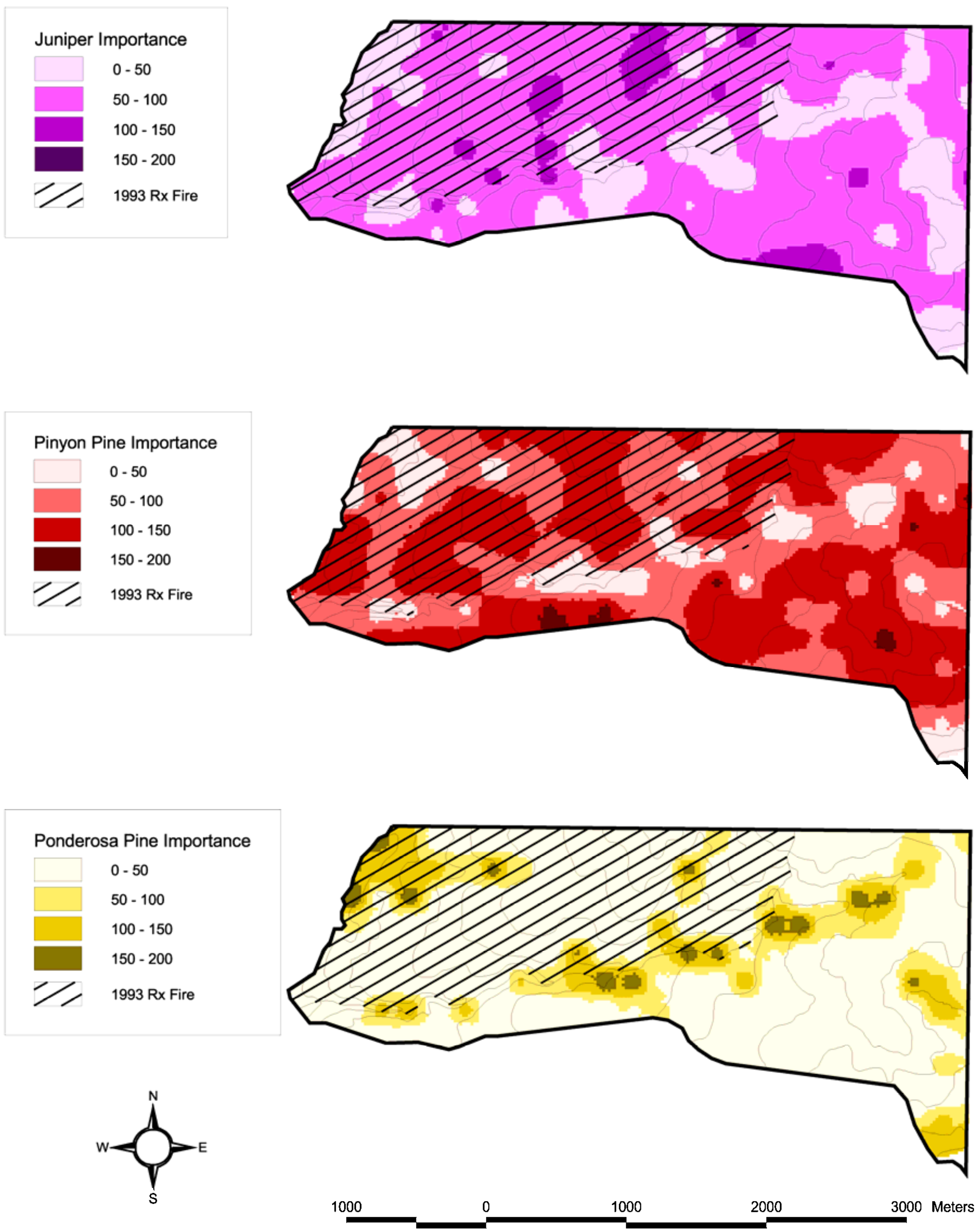

Figure 11. Map of importance values for overstory tree species at the Tusayan site. Importance values range from 0 (no trees of given species occur) to 200 (given tree species makes up 100% of both TPH and BA for sample). Crosshatching indicates area of 1993 prescribed fire.

Table 3. Mean number of trees per hectare (and standard error) by overstory species at the Canjilon site in 1890 and 2005. P-values ≤ 0.05 indicate statistically significant means between the two time periods.

Species	1890	2005	t	P
Jusc	50.5 (5.9)	105.9 (9.8)	7.04	<0.001
Juos	8.7 (3.6)	7.8 (3.2)	1	ns
Pied	390.3 (23.3)	621.5 (36.8)	7.89	<0.001
Pipo	29.2 (6.2)	35.6 (8.2)	1.3	ns
Total	*478.8 (25.0)*	*770.7 (41.1)*	*9.19*	*<0.001*

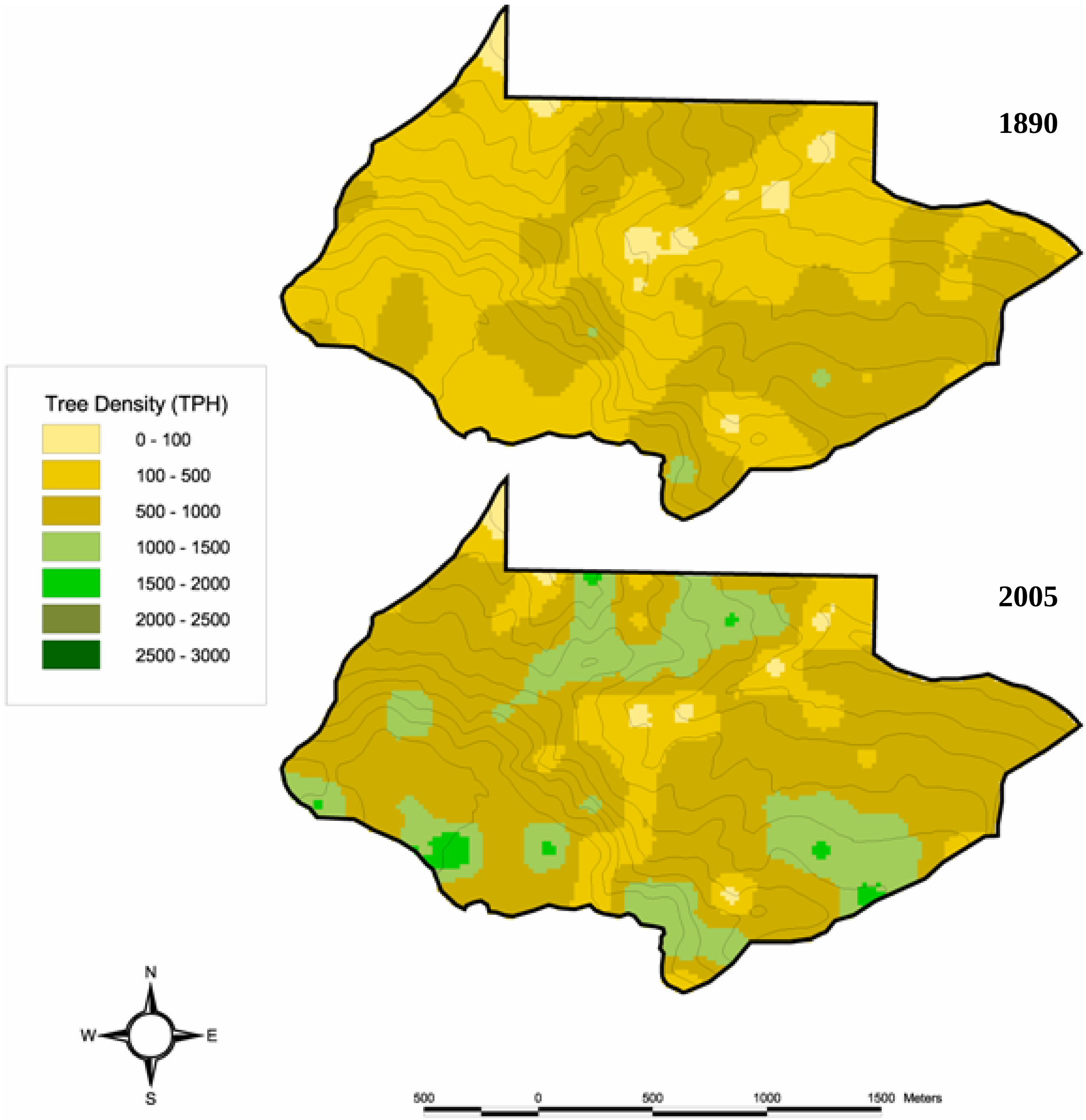

Figure 12. Map of reconstructed (1890) and contemporary (2005) tree density (TPH) at Canjilon site.

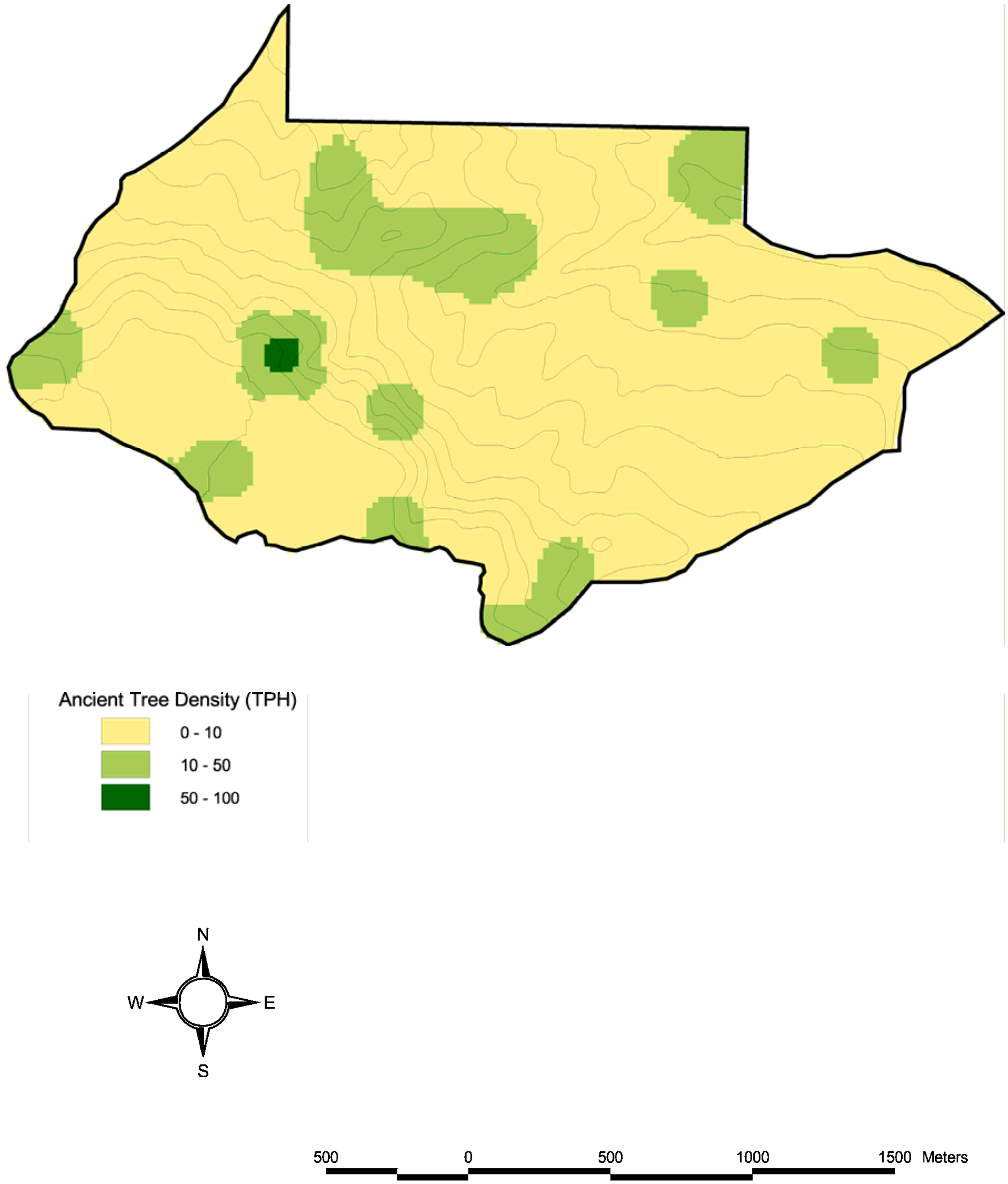

Figure 13. Map of density (TPH) of live, “old” trees (≥ 300 years of age) at the Canjilon site in 2005.

Maps of species importance values indicated that about half the landscape was comprised of patches dominated (importance = 150-200) by pinyon pine (Fig. 14). Rocky Mountain juniper was found at low importance (0-50) across about 80% of the site. Similarly, ponderosa pine was only locally important at Canjilon.

Reconstructed tree density ranged from 0 to 1,125 TPH with a mean of 479 TPH (SD = 257.4), which represented a significantly lower density than found in 2005 (Table 3). This change appeared to be due to increases in pinyon pine (59%) and Rocky Mountain juniper (110%). Neither ponderosa pine nor Utah juniper showed significant increases in density from 1890 to 2005. Interpolation indicated that 99% of the 1890 landscape was comprised of patches less than 1,000 TPH with more than half of the area in patches less than 500 TPH (Fig. 12).

Understory Structure

Tusayan

Twelve species of understory shrubs were observed on sample plots at the Tusayan site (Table 4). Of these the most frequently occurring species were sagebrush and cliffrose. On 10 sample plots, large (greater than 1.37 m in height and up to 23 cm DRC), dead and decadent cliffrose were noted, but we did not attempt to age these apparently old shrubs. Other species found on 8% or more of the plots were Apache plume and rabbitbrush. Interpolations indicated that relative shrub densities were 1.0 (< 2,500 individuals/ha) or lower across 50% of the study area (Fig. 15). Densities were noticeably low in the 1993 prescribed fire whereas outside the burn area patches generally had relative densities greater than 1.0 and several patches had densities greater than 2 (> 10,000 individuals/ha). Gambel oak density was typically sparse across the study site with scattered patches of higher density (i.e., > 2,500 stems/ha) (Fig. 15). No relationship between the 1993 prescribed fire area and oak density was apparent. Areas of higher oak density appeared to be associated with high ponderosa pine importance (see Figs. 11 and 15). Similar to oak distribution, there did not appear to be a pattern relating conifer regeneration densities and the 1993 prescribed fire area (Fig. 15). Just over 90% of the study area was comprised of patches of 0-1,000 or 1,000-2,500 seedlings per hectare. Most patches of high conifer regeneration appeared to occur in areas of high pinyon and/or juniper importance and lower seedling densities appeared to be associated with patches of high ponderosa pine importance (see Figs. 11 and 15).

Canjilon

At the Canjilon site, 8 species of shrubs were found on sample plots (Table 4). The most frequently occurring shrub was big sagebrush, which was found on 70% of the plots. A relatively large meadow dominated by big sagebrush was found in the center of the study area. Mountain mahogany and rabbitbrush were also found at relatively high frequencies (Table 4). Interpolations indicated that, in contrast to the Tusayan site, relative shrub densities were less than 1.0 over just 21% of the study area (Fig. 16). Sixty percent of the study area was comprised of patches with relative shrub densities from 1.0 to 2.0 (2,500 – 10,000 individuals/ha). Denser patches were found on 19% of the area. Gambel oak densities at the Canjilon site were relatively high and 45% of the area was comprised of patches of 1,000 or more stems per hectare. In six patches, oak densities were greater than 10,000 stems per hectare (Fig. 16). Similar to the Tusayan site, dense oak patches appeared to be associated with areas of higher ponderosa pine importance. Conifer regeneration was relatively low across the Canjilon site with 68% of the landscape showing 1,000 seedlings per hectare or less (Fig. 16). No clear pattern between regeneration density and overstory species importance was apparent.

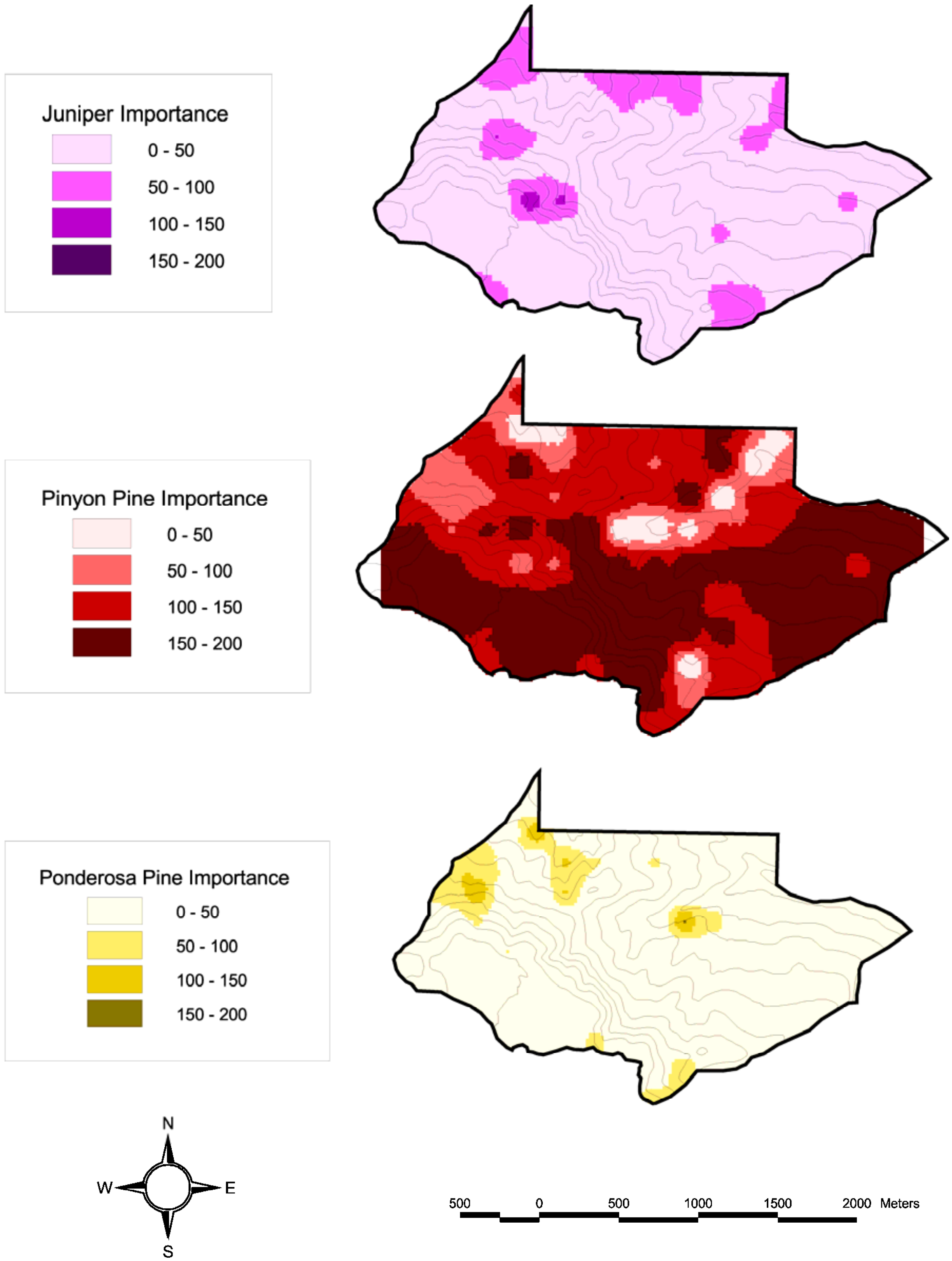

Figure 14. Map of importance values for overstory tree species at the Tusayan site. Importance values range from 0 (no trees of given species occur) to 200 (given tree species makes up 100% of both TPH and BA for sample).

Table 4. Shrub occurrence (% of plots) across Tusayan and Canjilon study sites.

	Occurrence (%)	
Species	Tusayan	Canjilon
Artemisia tridentata	48	70
Cercocarpus montanus	0	28
Chamaebatiaria millefolium	6	0
Ericameria nauseosa	8	11
Fallugia paradoxa	11	0
Gutierrezia sarothrae	1	<1
Mahonia fremontii	3	0
Mahonia repens	<1	2
Purshia mexicana	29	0
Rhus trilobata	3	<1
Ribes cereum	0	3
Symphoricarpos oreophilus	<1	3
Tetradymia canescens	3	0
Yucca baccata	1	0

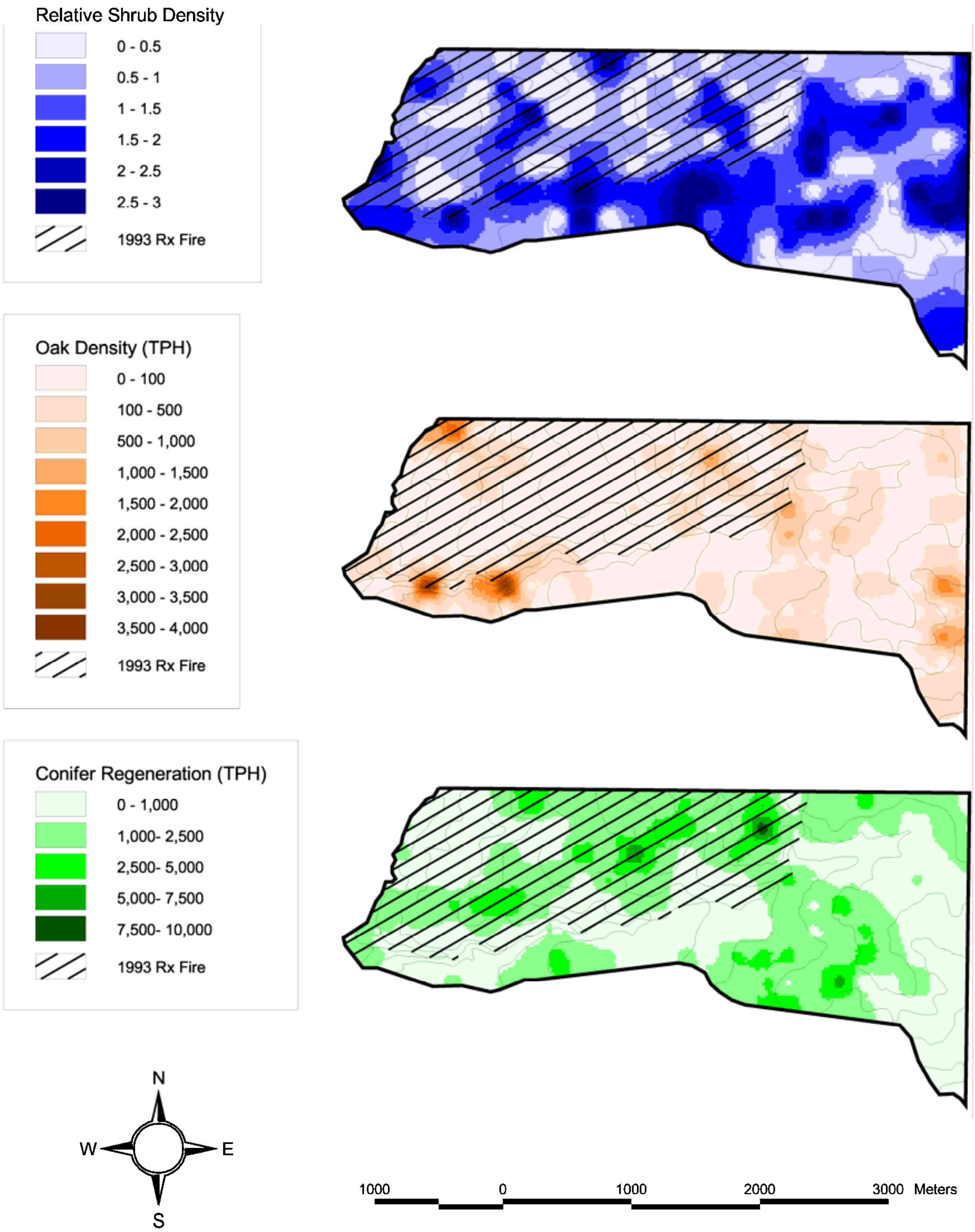

Figure 15. Maps of understory characteristics at the Tusayan site. Crosshatching indicates area of 1993 prescribed fire.

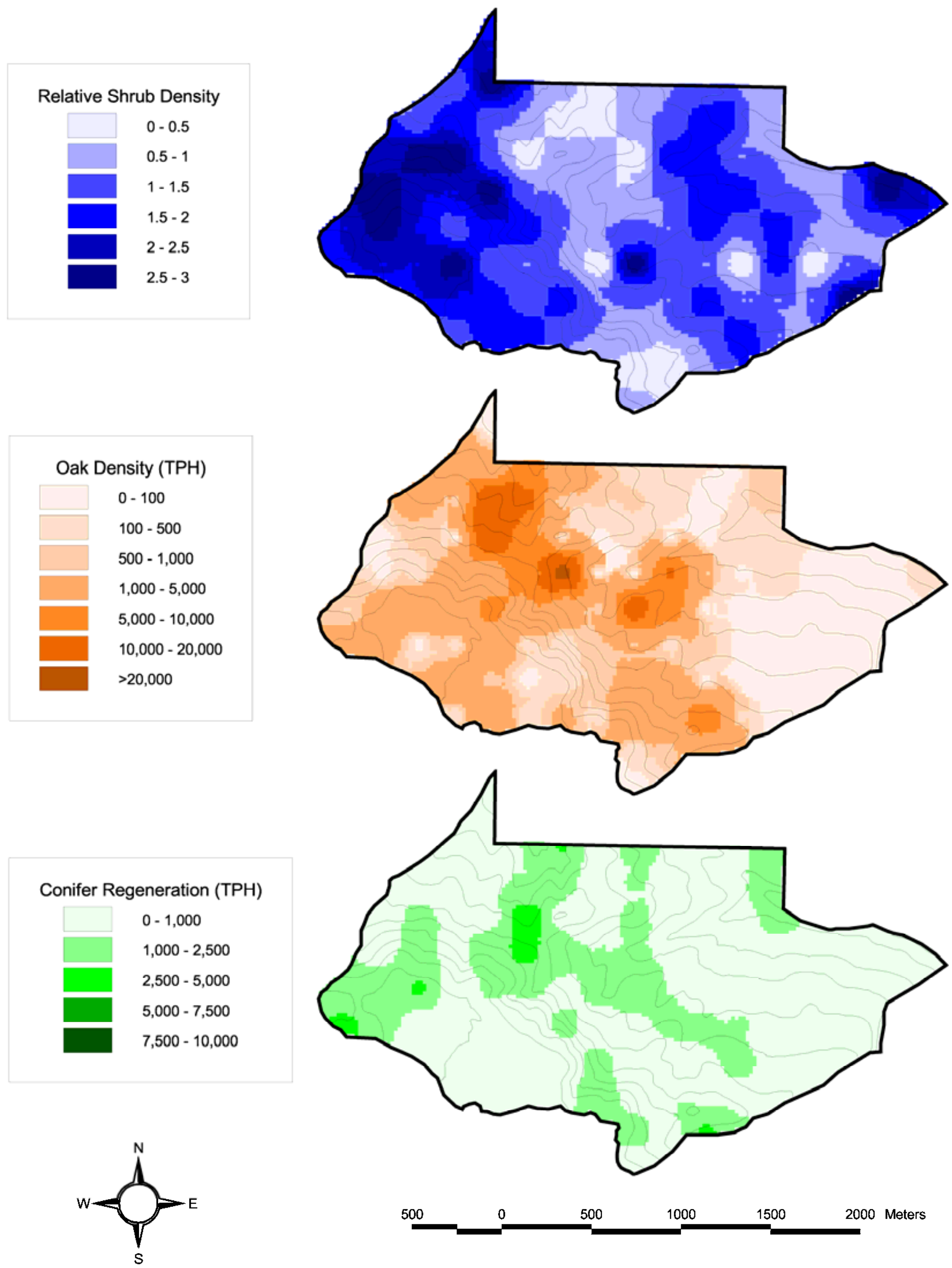

Figure 16. Maps of understory characteristics at the Tusayan site.

Overstory Stand Age and Fire Evidence

Tusayan

Interpolation of pinyon pine ages indicated that about 80% of the landscape was comprised of patches where the oldest pinyon trees were 200 years in age or greater (Fig. 17). The stand age class that made up the largest proportion (36%) of the study area was 250-300 years. This age class also appeared to have the largest mean patch size (30 ha). Mean patch sizes of all other age classes were less than 5 ha except for the 200-250 year class, which had a mean patch size of 13 ha. Pinyon pine age appeared to be youngest in areas of high ponderosa pine importance (see Figs. 11 and 18). Relatively large stands where pinyon trees were 300 years of age or older were present within the 1993 prescribed fire area.

Locations of charred tree structures overlaid on the Tusayan map of maximum pinyon age indicated little relationship between fire evidence and stand age (Fig. 18). Areas of high char density were found adjacent to stands with trees up the 300 years of age. In addition, partial tree cross sections showing multiple fire scars were collected in both areas with high ponderosa pine importance (i.e., younger pinyon ages) as well as areas with old pinyon pine trees (Fig. 18).

Data provided by Tusayan Ranger District personnel indicated that 16 fires were recorded at the study site from 1970 to 2004. Twelve of the fires were lightning-caused and the remainder was human-ignited from campfires, smoking, or arson. Two fires were started in June, seven occurred in July and the rest were in August or a later season of the year. One fire was 0.25-9.9 ac in size, the rest were less than 0.25 ac.

Canjilon

Interpolation of maximum pinyon age at the Canjilon site showed a narrower range of stand ages than was found at Tusayan (Fig. 19). Stands with maximum pinyon age of 200-250 yr and 250-300 yr had mean patch sizes of 24 ha and 79 ha, respectively. Younger (<200 yr) and older (>300 yr) stands had mean patch sizes less than 10 ha. The oldest stands (>250 years) were located at the upper elevations along the southern edge of the study site (Fig. 20). Young stands were located near a prominent big sagebrush meadow in the center of the study area (Fig. 20).

In contrast with the Tusayan site, relatively little fire evidence in the form of charred tree structures and fire scars was found near the older pinyon stands (Fig. 20). In these stands we did find “cat-face” injuries with multiple fire scars, but the majority of charred tree structures and fire scars were located at lower elevations near the northern edge of the study site. A high concentration of charred tree structures was found on the eastern edge of the study site near the rim of the Mesa de Las Viejas and stand age was relatively young in this area (Fig 20).

Modern fire maps indicated only four fires recorded from 1975 until 2005; two of these fire occurred in 1970s and the others occurred in the 1980s. All fires were lightning-caused and three occurred in May-June and the other occurred in August. None of the fires were greater than 0.25 ac in size.

DISCUSSION

Evidence of Historical Surface Fires

Tusayan

Fire scar analysis indicated that surface fire recurred at intervals of 7.2-7.4 years (WMPI; MFI = 10.9-11.6 yr) in ponderosa pine forest communities at Tusayan. Although fire samples

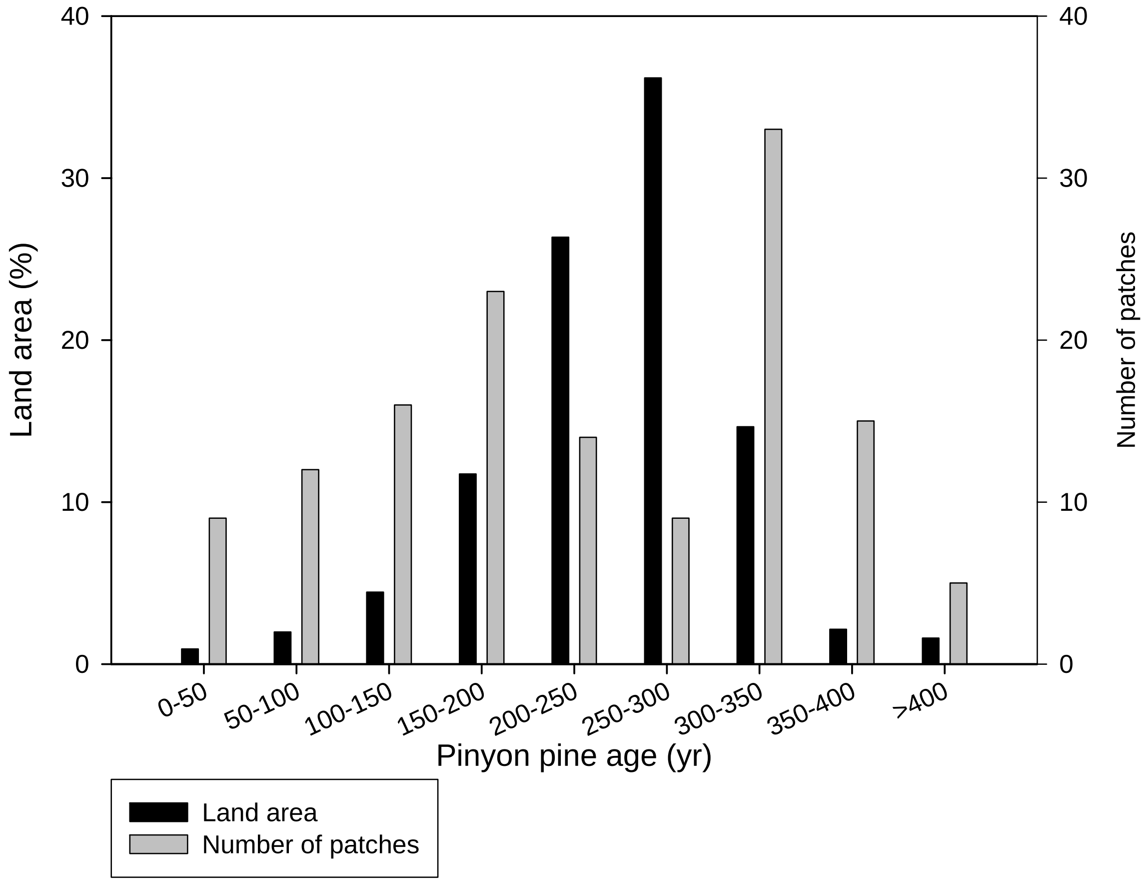

Figure 17. Land area and number of patches having similar pinyon pine age (maximum) at Tusayan. Patches of similar pinyon pine age were treated as stands to investigate evidence of stand-replacing fire.

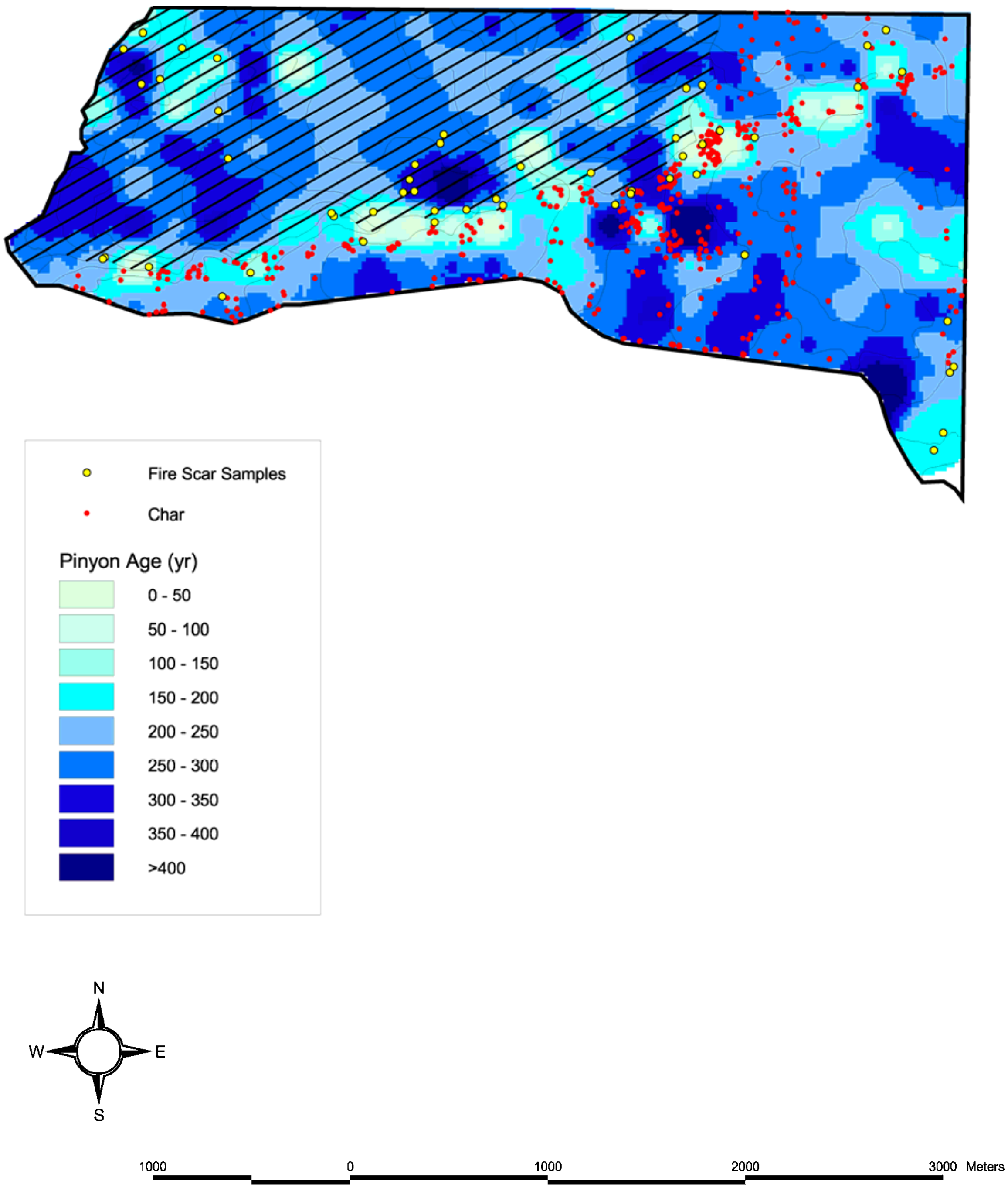

Figure 18. Map of maximum pinyon pine ages found on sample plots at the Tusayan site. Locations of fire scar samples (partial cross-sections) and charred tree structures (“char”) are shown. Crosshatching indicates area of 1993 prescribed fire.

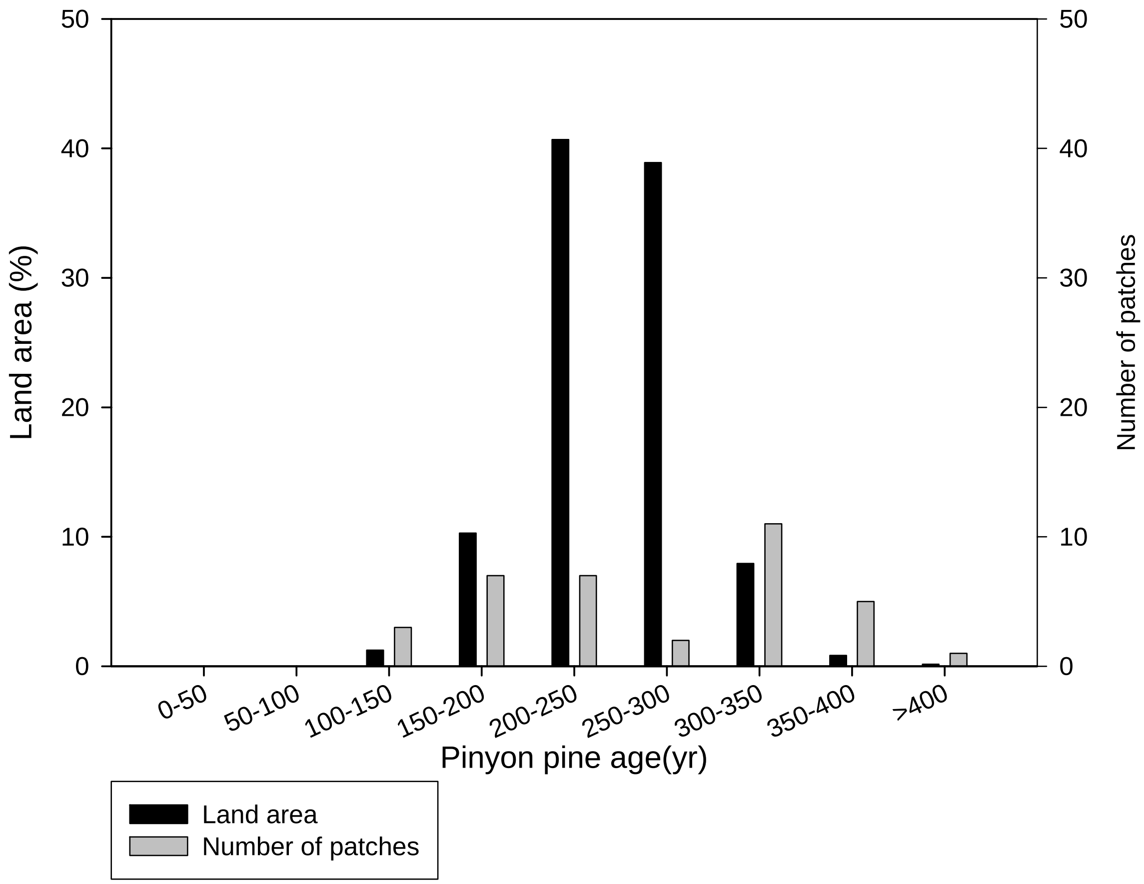

Figure 19. Land area and number of patches having similar pinyon pine age (maximum) at Canjilon. Patches of similar pinyon pine age were treated as stands to investigate evidence of stand-replacing fire.

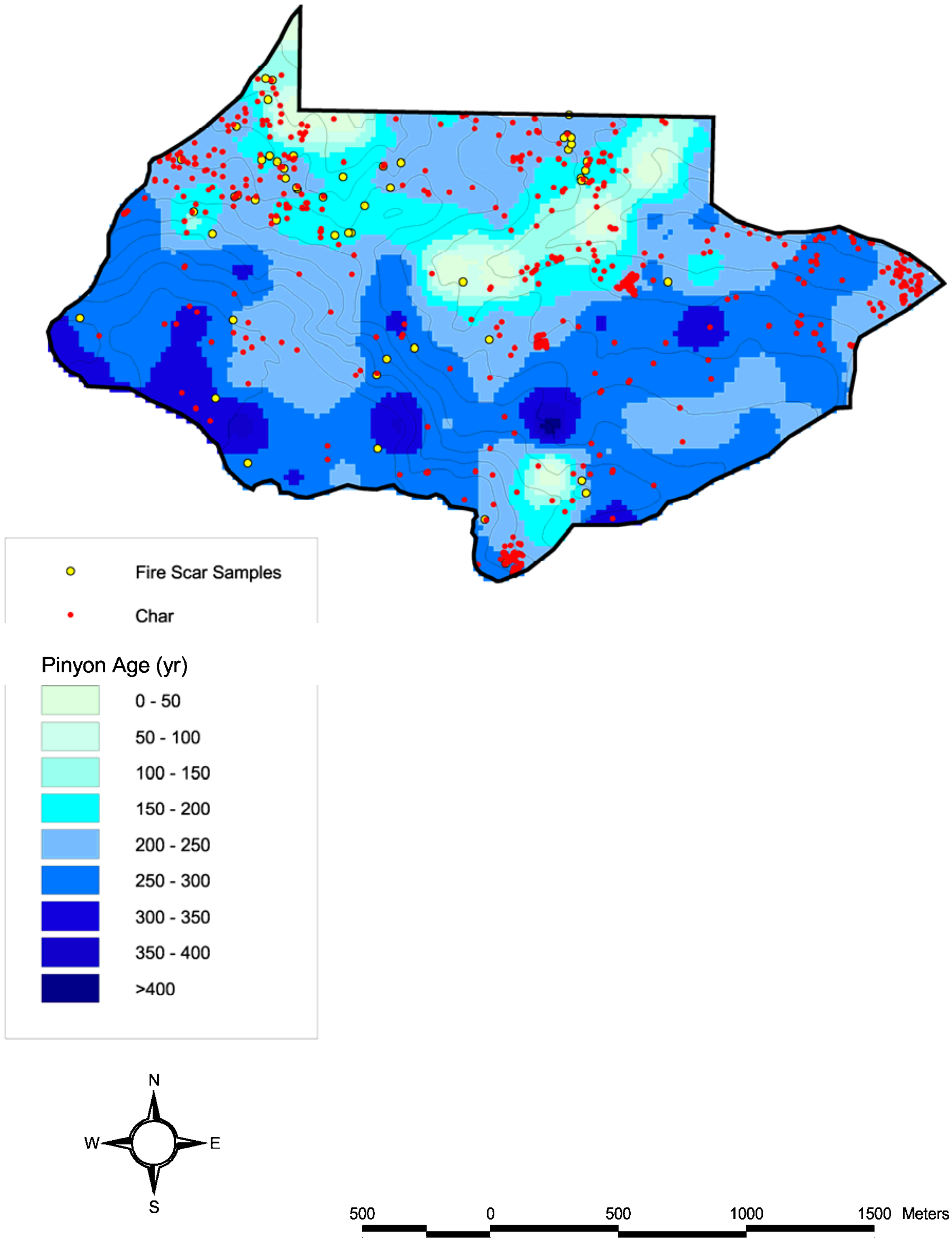

Figure 20. Surface map of maximum pinyon pine ages found on sample plots at the Canjilon site. Locations of fire scar samples (partial cross-sections) and charred tree structures ("char") are shown.

from pinyon and juniper trees were collected, we found difficulty crossdating these species, particularly juniper. At the Tusayan site, it was clear that surface fire historically burned through the canyons draws dominated by ponderosa pine forests. It was not clear, however, whether these fires burned as surface fires through the pinyon-juniper uplands. Other studies have described historical surface fire regimes for pinyon-juniper woodlands occurring with other vegetation types at upper and lower ecotones. For example, Gruel (1999) examined fire scars on ponderosa, Jeffrey (*Pinus jeffreyi*), and pinyon pine trees and concluded MFI ranged 8-20 years for three pinyon-juniper sites in the Great Basin. Miller and Rose (1999) studied fire scars on ponderosa pine trees to infer MFI of 12-15 years for western juniper (*J. occidentalis*) woodlands and sagebrush steppe communities in southern Oregon. In northeastern Wyoming, Perryman and Laycock (2000) examined fire scars on ponderosa pine and Rocky Mountain juniper trees and concluded that fire-free intervals averaged 6.7-7.9 years for a conifer woodland-northern mixed-grass prairie ecotone.

Point intervals are likely to be conservative estimates of fire since each fire that occurs may not be recorded as a scar on a particular tree and subsequent fires may obscure scars (Brown et al. 2001, Van Horne and Fulé 2006). Although point intervals based on ring-counted samples do not allow examination of fine-scale temporal changes in fire history, they can provide insight concerning long-term patterns occurring over decades to centuries. Fire scar dates on samples at Tusayan were crossdated to around 1500; therefore, we assumed point intervals represented fire recurrence for the last 500 years at this site. The overall PMFI of 41.6 years suggested that light to severe surface fires were an important component of the historical disturbance regime (Heinselman 1981). Point intervals have been used by other researchers to estimate fire history of pinyon-juniper woodlands. For example, Brown et al. (2001) crossdated fire scars on seven pinyon pine trees and reported MPFI of 27.5 years for three pinyon-juniper sites in the Sacramento Mountains of southern New Mexico. Leopold (1924) used ring counts to conclude that fires historically recurred on 10-year intervals for alligator juniper (*J. deppeana*) savannas of southern Arizona.

When stratified by species, point intervals on Tusayan samples suggested that fire frequency varied in relation to microsite differences. For example, ponderosa and pinyon pine fire intervals were similar and less than <50 years, whereas juniper intervals tended to be longer than these species with means up to 100 years. Although crossdating fire scars on juniper wood was not possible in this study, other researchers have apparently been successful at determining fire dates on similar species. For example, Burkhart and Tisdale (1976) found that scars on 50 western juniper (*J. occidentalis*) trees suggested surface fire return intervals of about 11 years in southwestern Idaho. Similarly, Young and Evans (1981) examined fire scars on 28 western juniper trees in northern California and reported evidence of extensive surface fires in the 1600s, 1700s, and 1800s. Maps of species importance in our study indicated that juniper was generally confined to upland sites whereas pinyon pine was found in relatively greater importance along with ponderosa in the canyons. Our interpretation of these data is that surface fires burned with relative regularity through ponderosa and pinyon pine communities and less frequently spread onto upland areas where pinyon and Utah juniper were more important. Although it is reasonable to hypothesize that fires spread into upland communities during periods of particularly widespread fire, we could not clearly associate known fire dates with scars found on juniper trees. Fires that historically carried into the pinyon-juniper communities apparently did not result in extensive crownfire and large patches of tree mortality.

Canjilon

At Canjilon, fire scar samples were collected from a more balanced number of ponderosa and pinyon pine tree structures and were found on various microsites, distributed more or less generally across the study area. Therefore, the composite WMPI of 11.1 years could be a reasonable estimate of composite historical fire frequency at this site as a whole, not only the ponderosa-dominated areas. However, WMPI and PMFI (81 yr) differed by a greater proportion at Canjilon than at Tusayan, suggesting that many fires may have been small in extent. The fire history graph (Fig. 9) shows the long periods between any recoded fires, indicating that a composite WMPI statistic is misleadingly short in this case. In contrast to Tusayan, point intervals for ponderosa and pinyon pine samples at Canjilon were found in the 101-300 year class. This suggests fires characterized as belonging to a regime of long return interval crown fires and severe surface fires in combination (Heinselman 1981). In other studies, historical fire regimes of mixed-severity fires have been reported. For example, Brown et al. (2001) found fire scar evidence of low to moderate severity surface fire for pinyon-juniper woodlands in New Mexico, yet also described evidence of stand replacing fire in the form of young stands with few older living trees. It should be noted that small to moderately sized areas of charred remains do not necessarily indicate historical fires that resulted in tree mortality. Although it is clear that multiple fire scars on a tree indicate sublethal events (i.e., surface fires), it is not clear whether a charred structure represents a burned snag or a live tree that was killed by fire. Several widespread mortality events are known to have occurred in the 1900s, when drought and insect infestation resulted in landscape-scale mortality of pinyon pine trees (Breshears et al. 2005, Betancourt et al. 1993). Fire occurring following such an event could result in large areas of charred remains and appear to be the agent of mortality. Despain and Mosely (1990) also found evidence of historical mixed-severity fires on a site in northern Arizona where both surface fires and more severe fires occurred. Scars of seven recent (post-1890) fires were found at Canjilon and US Forest Service records indicated four others. None of these fires resulted in significant tree mortality.

Evidence of Stand Replacing Crown Fires

Tusayan

Scarred trees and charcoal evidence at the Tusayan site indicated that fire was ubiquitous over the last 500 years. Little evidence was found, however, to indicate that severe fires were extensive over this period. We base this interpretation on stand ages, prevalence of old trees and shrubs, characteristics of charred tree structures, and reconstruction of historical conditions. Stands (i.e., patches of similarly aged pinyon pine) were generally small (< 30 ha) and represented a broad range of ages. This suggested that fires were often small in extent and probably occurred as patchy surface fires to mixed-severity fires that killed groups of trees or small stands. Floyd et al. (2000, 2004) examined fire records, stand ages, and ages of Gambel oak sprouts of a pinyon-juniper and shrubland ecosystems at Mesa Verde and estimated natural fire rotation periods of up to 400 years. These researchers found burned area extents of up to 3,461 hectares for stand-replacing fires that burned in the early 1800s. In one area that burned within the last 150 years, standing remains of charred junipers were observed (Floyd et al. 2000). Similarly, Arnold et al. (1964) described a large area with numerous charred juniper snags near Supai, Arizona (west of our Tusayan study site). Judging from the age of a pinyon tree growing near a snag, this site had apparently burned around 1875 and resulted in conversion of pinyon-juniper woodland to a big sagebrush community. Nearly 80 years after the fire, Arnold et al. (1964) found that total tree cover on the Supai burn was just 0.3%. At Mesa Verde, Floyd et al. (2000) concluded that successional processes were slow, noting a lack of conifer regeneration in recently burned areas. Erdman (1970) suggested recovery to "climax" pinyon-juniper vegetation after fire at Mesa Verde may take about 300 years. At Tusayan, we found no patches >30 ha that were apparently recovering after severe fire.

Floyd et al. (2004) surmised that occurrence of numerous old pinyon and juniper trees indicated a very long fire return interval and a stand-replacing fire regime. Similarly, Romme et al. (2003), hypothesized that trees greater than 300 years in age would be relatively abundant in pinyon-juniper ecosystems historically regulated by low frequency, high severity crown fires. In contrast, Brown et al. (2001) concluded that severe fire within the last century produced numerous dead and downed trees, stands of mainly young trees, and an absence of old trees. At the Tusayan site, we found many (26 TPH) old trees (>300 yr) but few large patches of similarly aged trees. In addition, no large areas of charred tree structures were found at the Tusayan site with the exception of the 1993 prescribed fire area.

Overall increases in stand density, as indicated by our reconstructions, are likely due to a combination of factors including land use history as well as climate. We recognize that more work is needed to develop rigorous reconstruction methods for pinyon-juniper ecosystems. As has been widely discussed elsewhere, it is likely that increases in ponderosa pine density resulted largely from historical grazing and fire exclusion (Cooper 1960, Covington and Moore 1994, Fulé et al. 1997, Moore et al. 1999, Allen et al. 2002, Noss et al. 2006). Changes in pinyon density were evident although we are not certain how successful we were at identifying all historical evidence since unburned pinyon trees tend to decompose relatively quickly (Kearns et al. 2005). Decreases in juniper from 1887 to 2004 are likely due natural mortality, fuelwood cutting and a reduction in microsites for regeneration. Large dead and decadent cliff rose plants found across the site may evidence more open conditions that once existed and long (e.g., 100 years) periods free of severe fire (Young and Evans 1981). We suggest that historical fires at Tusayan were of mixed severity and kept stands open, yet patchy, but did not result in extensive areas of tree mortality.

Canjilon

At Canjilon, relatively more evidence for severe historical fires existed than was found at Tusayan. For example, stands of similarly-aged pinyon at Canjilon were relatively large. Age classes from 200 to 300 years made up almost 80% of the landscape yet less than 15 patches comprised these classes. Few young patches or older patched were found. Furthermore, old trees were relatively scarce at the Canjilon site, although Gambel oak density was very high in several areas. Although we did not attempt to determine age of oak sprouts at Canjilon, Floyd et al. (2000) used stem as an indicator of fire date in pinyon-juniper woodlands of southwestern Colorado. We did not attempt to calculate a natural fire rotation for the Canjilon study site since we also found evidence of surface fire in the form of fire-scarred trees.

Spatial arrangement of stands and fire evidence at Canjilon suggested areas where severe fire likely occurred and woodland conditions were presently reestablishing or encroaching on new microsites. For example, on the eastern edge of the study site near the rim of La Mesa de Las Viejas, we observed a patch of young pinyon pine and scattered charred tree structures. It also appeared that the stands at the lower elevations of the site were the youngest. These stands were located near the prominent big sagebrush meadow toward the center of the study site. These patterns were likely due to fires that burned up steep slopes and came over the rim of the Mesa and fires that occurred in the shrubby meadows and spread into the surrounding pinyon-juniper woodlands. Large increases in pinyon density since 1890 in some areas may represent recovery after historically severe fire. Densification of pinyon-juniper woodlands and encroachment of woody vegetation into shrublands and grasslands are well documented (Tausch et al. 1981, Jacobs and Gatewood 1999, West 1999, Romme et al. 2003). Increases in tree density have led to losses of understory plant species abundance and diversity, increased rates of erosion, and increased susceptibility to stand-replacing wildfire. In other forest types of the western United States, similar changes in structure have been linked to fire exclusion, livestock grazing, and logging near the time of EuroAmerican settlement (ca 1870) (Bonnicksen and Stone 1982, Covington et al. 1994, Swetnam and Baisan 1996, Fulé et al. 1997, Baisan and Swetnam 1990, Mast et al. 1999, Moore et al. 2004). These factors, in combination with climate and atmospheric changes (e.g., wet, mild winters in the early 1900s; post-1950 increases in CO_2 levels), may be responsible for pinyon-juniper expansion and densification on historical pinyon-juniper savannas (Burkhardt and Tisdale 1976, Young and Evans 1981, West 1999, Miller and Tausch 2001). In historically forested sites, tree density increases may represent long-term processes of recovery after infrequent, natural disturbance (Erdman 1970, Romme et al. 2003, Floyd et al. 2004). Fire scar and US Forest Service records indicated occurrence of recent fires on the Canjilon study site, but these fires have apparently not produced woodland openings or thinned pinyon trees.

CONCLUSIONS

Although we intentionally selected the Tusayan and Canjilon study areas to be as similar as possible in terms of soils, climate, and vegetation, we found distinctly different patterns of forest structure and fire history at the two sites. At Tusayan, evidence of frequent surface fire was found in canyons and draws whereas fire scars and tree age on the pinyon-juniper uplands suggested that patchy, mixed severity fires occurred at less frequent intervals. Fire frequency appeared related to microsite conditions and intervals appeared longest for Utah juniper communities. Relatively little change had occurred in overall tree density since 1887, although ponderosa pine density had increased substantially. Abundance of old trees on the Tusayan site suggested that few large scale disturbances had occurred in several centuries. Historical light surface fires were less evident at Canjilon and long point fire intervals suggested infrequent crown fires or severe surface fires regulated this ecosystem. Stand ages and charred tree structures led us to believe that severe fires occurred at Canjilon, particularly along the eastern edge of the study site and near big sagebrush meadows. A lack of old trees and recent increases in tree density suggested that woodland vegetation was encroaching into areas that were previously more open. We surmise that these areas were historically maintained by moderately severe fires.

IMPLICATIONS

Fire undoubtedly played a central role in controlling the historical structure and function of pinyon-juniper ecosystems; however, there is still great uncertainty regarding characteristics of natural fire regimes in many locations (West 1999, Baker and Shinneman 2004). Uncertainty arises from two main sources: 1) high variability in structure and composition across the geographic range of the type (West 1999), and 2) past studies have not made use of the full array of potential research methodologies in analysis of historical fire regimes and few high quality data sets are available with which to confidently evaluate patterns or draw conclusions (Baker and Shinneman 2004). Research describing pinyon-juniper fire regimes is critically needed for assessment of ecosystem health and development of reference conditions for ecosystem management or ecological restoration programs (Morgan et al. 1994, Landres 1999, Moore et al. 1999). In this study, we used multiple methodological approaches to assess historical patterns of fire and woodland structure on two southwestern pinyon-juniper sites: Tusayan and Canjilon. Fire interval analysis based on crossdating fire scars provided the most detailed description of fire history; however this approach taken alone was problematic because juniper growth rings were extremely difficult to crossdate. Furthermore, these methods can only be used at the edges of severe burns, where trees were scarred rather than killed by fire. Additional data sources were needed in order to draw together multiple lines of evidence and more fully describe historical fire patterns. These data included stand age maps, inventories of fire evidence such as charred tree structures, and modern fire maps. A geographical information system (GIS) was used to assess spatial patterns of fire severity and extent. Results from this study suggest that exclusion of patchy, mixed severity fires at Tusayan has allowed stands to become more dense and homogenous, possibly increasing the site's susceptibility to severe fire of large extent. Canjilon may be more in line with its historical regime of larger stand replacing fires. Ecological restoration treatments at Tusayan would likely include targeted reduction in overstory tree density and periodic application of fire. Tree thinning in ponderosa pine communities is likely to reduce susceptibility to crown fire and reestablish historical disturbance patterns and structure. Opening small patches in woodland canopies may reinvigorate shrub populations that were an important component of the historical conditions. Use of prescribed surface fire in the canyons and draws is warranted and periodic fires may be used to maintain small openings in pinyon-juniper communities on the uplands. Care is needed to conserve the many old pinyon and juniper that exist at the site. At Canjilon, thinning young pinyon and Rocky Mountain juniper near big sagebrush meadows and at the lower elevations of the site is likely to reestablish historical patterns of woodland structure. In these communities, use of fire to create and maintain larger openings is likely to mimic historical patterns of disturbance and woodland dynamics.

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