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Historical and recent fire regimes in Piñon–Juniper woodlands on Mesa Verde, Colorado, USA

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Abstract

The fire history of Piñon–Juniper (*Pinus edulis–Juniperus osteosperma*) woodlands in much of the southwestern United States is poorly understood, and as a result, fire management decisions are being made without a rigorous ecological underpinning. We investigated the historic fire regimes in Piñon–Juniper woodlands on the Mesa Verde cuesta utilizing stand and age structures. All Piñon trees in eight stands were aged and stand age was extrapolated to the surrounding landscapes using digital imagery, creating a time-since-fire map of the 1995 landscape. Six sampled stands were over 400 years, while two were between 200 and 300 years. Stand-replacing fire with a rotation of 400 years or longer characterized this Piñon–Juniper landscape before 1995; low-severity surface fires apparently have never been an important component of the fire regime in Mesa Verde. Superposed epoch analysis revealed that large fires occur following significantly low precipitation in May or in the winter (October–March) preceding a summer fire season. Since the mid-1990's, a severe drought has characterized climate in this region, but the recent drought is similar to previous drought periods since 1950. A combination of canopy fuel build-up during two wet decades before 1995 and the current drought conditions has resulted in unprecedented fire activity (six large wildfires between 1996 and 2003) when compared with the reference period 1700–1900. We may be witnessing a unique period in the ecological history of the southwest, a period when vegetation patterns are being altered over extensive areas within a very short time. If the current drought continues, we ultimately may lose much of the old-growth Piñon–Juniper woodland in the southwest. We emphasize however, that these changes are not due to fire suppression or other direct human intervention but rather result from natural ecological responses to climatic variability. Therefore, our data provide no ecological justification for aggressive management activities such as mechanical fuel reduction or prescribed burning, except in the immediate vicinity of vulnerable cultural resources.

Keywords: Piñon–Juniper fire history; Petran chaparral; Woodland fire rotation; Climate effect on fire regime

1. Introduction

Piñon–Juniper forests and woodlands (*Pinus* spp. and *Juniperus* spp.) cover a vast area in the western and southwestern United States, and are vitally important for biodiversity, aesthetics, and commodity production (Wangler and Minnich, 1996; Miller et al., 1999; Mitchell and Roberts, 1999; West and Young, 2000; Floyd, 2003). Unfortunately, the tremendous range of variation in natural disturbance regimes and post-disturbance dynamics of this extensive vegetation type is not well understood or

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appreciated. It is often assumed that Piñon–Juniper stands burned frequently before 1900, and that 20th century fire suppression has led to abnormally dense stands and severe fire behavior. While this scenario could be accurate in some areas, Piñon–Juniper exhibits a wide variety of fire regimes and stand dynamics, including many systems that were historically characterized by infrequent, high severity fire regimes and naturally dense stands (Romme et al., 2003; Baker and Shinneman, 2004). A major reason for our inadequate understanding of Piñon–Juniper disturbance dynamics is the methodological difficulty of reconstructing fire history in these systems. Fire scars tend to be rare or absent, making precise reconstruction of prehistoric fire history difficult or impossible. The lack of fire scars is partially due to the fact that Piñon and Juniper are both easily killed by fire, and also because historical fires in many areas were very infrequent or were of high severity (Romme et al., 2003; Baker and Shinneman, 2004). Moreover, regeneration of Piñon and Juniper tends to be slow and variable after fire. Unlike lodgepole pine and some other forest types, where fires usually are followed by prompt establishment of an even-aged cohort, Piñon and Juniper may require many decades to re-establish new populations following a stand-replacing fire (Floyd et al., 2000).

The need for better knowledge about prehistoric fire regimes in Piñon–Juniper woodlands is becoming increasingly urgent, as land managers begin to implement ambitious policies intended to mitigate wildland fire hazards across the western US by means of fuel reduction (Healthy Forests, 2002). To help identify priorities for fuels treatments, public lands managers are classifying major vegetation types into ‘‘condition classes’’ which reflect the nature of the prehistoric fire regime and the degree to which that fire regime has been altered during the last century (Schmidt et al., 2002). These classifications typically regard Piñon–Juniper vegetation as having burned frequently in the past and as having ‘‘missed’’ several fires that would have occurred in the last 100 years had fire suppression not occurred (e.g. Schmidt et al., 2002). The occurrence of several large, severe fires during the last decade in Piñon–Juniper vegetation often is taken as further evidence that these ecosystems have become degraded and are in immediate need of intensive treatment (usually involving mechanical tree removal and/or prescribed low-severity fire) to restore them to a more natural condition. However, without an adequate understanding of the historical range of variability of Piñon–Juniper vegetation, it is impossible to assess the current state of these ecosystems or to determine whether recent fire sizes and behaviors have been normal or abnormal. Indeed, a systematic review of the literature (Baker and Shinneman, 2004) uncovered no empirical support for any sweeping generalization that Piñon–Juniper vegetation now lies outside the historical range of variability. On the contrary, infrequent severe fires appear to be the norm for many Piñon–Juniper systems. Therefore, the current aggressive effort to ‘‘restore’’ Piñon–Juniper woodlands may be misguided or even damaging to ecological integrity (Landres et al., 1999; Swetnam et al., 1999; Cole, 2000; Romme et al., 2003; Baker and Shinneman, 2004).

Mesa Verde National Park (MVNP) is one of many national parks and monuments in the southwestern United States where Piñon–Juniper woodland is a major vegetation type and fire is an urgent management issue. The park is situated on a prominent cuesta in southwestern Colorado (Fig. 1), and supports vegetation similar to many other parts of the Colorado Plateau (which encompasses portions of Colorado, Utah, New Mexico, and Arizona). Five large, high-intensity fires in the last decade have burned most of the park and a large adjacent portion of the Mesa Verde cuesta. These fires threatened sensitive cultural resources, produced substantial post-fire erosion and sedimentation, and caused the park to be closed to visitation for several weeks. Two contrasting interpretations of these recent large fires are plausible. First, they may be natural events of a kind that has always occurred during very dry periods such as the southwest is now experiencing. Alternatively, the size and frequency of recent fires may be unprecedented in the ecological history of Mesa Verde, indicating that the system has shifted into a new state that lies outside the historical range of variability. The management implications of these two contrasting interpretations are very different, yet neither view can be verified or rejected without a good understanding of Mesa Verde’s historical fire regime. Because the situation in Mesa Verde is similar to that of many other areas in the southwest, a reconstruction of fire history and an assessment of recent fire behavior in Mesa Verde can

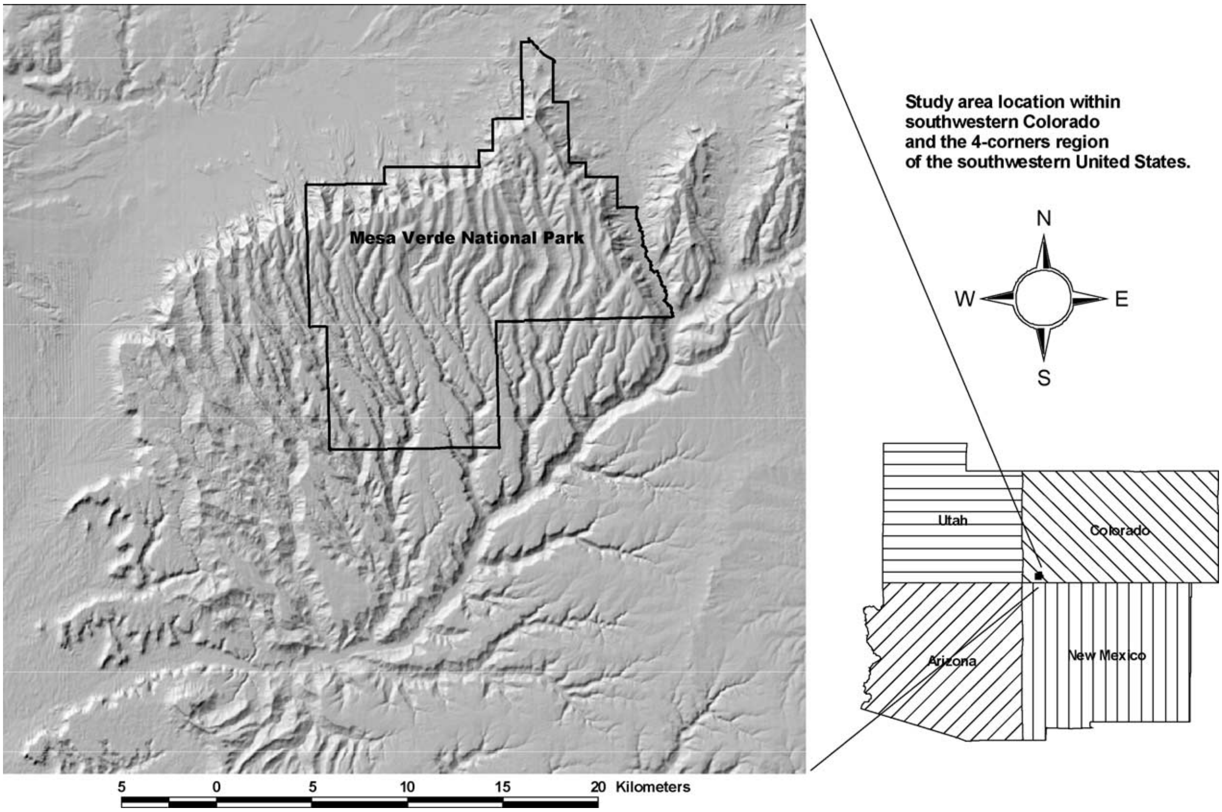


Fig. 1. Location and topography of the Mesa Verde cuesta and Mesa Verde National Park in southwestern Colorado, USA.

help in understanding and developing sound fire management policies throughout the larger region.

The northern portion of MVNP is dominated by tall mountain shrublands (often called petran chaparral) which have developed following fires during the last 200 years (Erdman, 1970). Floyd et al. (2000) mapped the major fires since the 1840s in the shrubland portion of MVNP, based on post-fire cohorts of re-sprouting oak (*Quercus gambelii*), and determined that the average fire return interval in shrublands was about 100 years prior to the 20th century. Although few fires occurred in the early 20th century, several large fires occurred in the second half of the 20th century. A graph of cumulative time-since-fire indicates little difference between late-19th century and late-20th century area burned per decade. Thus, the fire exclusion policy in effect since the Park's establishment in 1906 probably has prevented many fires that would have been small or moderate-sized (<100 ha) if not suppressed, but had little impact on the large fires (hundreds or thousands of hectares) that ignited under conditions of extreme drought and high wind. These latter kinds of fires, uncontrollable even with modern fire suppression technology, are infrequent but account for most of the area burned in a century—a situation similar to many boreal forests (Johnson, 1992), subalpine forests (Romme, 1982), and chaparral vegetation (Moritz, 1997; Keeley and Fotheringham, 2001—but see Minnich, 2001).

Floyd et al. (2000) dealt primarily with the shrublands in the northern portion of MVNP. However, fire history and stand ages in the Piñon–Juniper woodland that covers much of the southern portion of the park and the surrounding cuesta are largely unknown. Much of the Piñon–Juniper woodland in MVNP appears very old, with large trees (50–100 cm diameter at base), high tree density and basal area, and little or no evidence of fire scars or charred wood

(Floyd, 2003). In our previous work, we determined from a small sample of tree ages that two old-appearing Piñon–Juniper stands had indeed escaped major disturbance for many centuries (Floyd et al., 2000), but we had no information for other areas outside the mountain shrubland portion of the park. Mesa Verde's Piñon–Juniper woodlands appear at first glance to be uniformly old, dense, and vulnerable to severe fire. However, a closer inspection reveals considerable variability in the structure of these woodlands. One finds unique density and diameter distributions in different areas, and some stands appear to be developing after stand-replacing disturbances that occurred at some undocumented time in the past.

Despite extensive searching, we have found no fire-scarred trees in the Piñon–Juniper woodlands of Mesa Verde (Floyd et al., 2000; Romme et al., 2003). Therefore, we reconstructed fire history using a less precise method based on current tree age and diameter distributions. Reconstruction of woodland history from static age distributions may be problematic, and so we were very conservative in our interpretations. Johnson et al. (1994) argued that the only reliable ways to fully understand forest dynamics are to: (i) observe a forest over time; or (ii) reconstruct past age structures from both living and dead material, thereby accounting for past mortality as well as extant individuals. Unfortunately, neither of these approaches is feasible in the Piñon–Juniper woodlands of Mesa Verde and many other areas dominated by Piñon–Juniper woodland in the southwest. A preliminary estimate of the fire rotation in Mesa Verde is on the order of 400 years, and individual stands may exceed 600 years in age (Floyd et al., 2000), so following an individual stand over time is not possible. Dead Juniper is very persistent, but difficult to date accurately whereas Piñon cross-dates readily but decomposes more rapidly than Junipers after death. Despite these limitations, we were able to distinguish several broad stand age classes in Piñon–Juniper stands, as described below.

MVNP occupies only about 40% of the larger Mesa Verde cuesta, although the vegetation and synoptic climate are generally similar throughout the cuesta. Thus, the entire 53,870 ha cuesta represents a more appropriate ecological unit for analysis than the park area per se (21,433 ha). Therefore, we assessed fire history both for MVNP alone and again for the entire cuesta to examine how our interpretations of fire rotation and landscape dynamics may differ at these two different spatial scales. Given the inherent constraints of reconstructing fire history in the Piñon–Juniper vegetation type (Baker and Shinneman, 2004), our resulting estimates of fire dates and fire extents prior to the mid-1800s are relatively imprecise; however, we emphasize that even approximate data of this kind are generally lacking for Piñon–Juniper woodlands in the western United States. Moreover, the general picture that emerges of this area's historical fire regime provides a critical historical context for understanding recent large fires and for developing ecologically-based fire management goals and strategies for the park (Swetnam et al., 1999).

To evaluate the recent large fires in Mesa Verde within an appropriate historical context, this study had four objectives:

- document the full range of stand ages in the Piñon–Juniper woodlands of MVNP;
- map the extent of major fires throughout MVNP and the Mesa Verde cuesta during the last 300 years;
- identify the climatic conditions associated with large, severe fires, and the frequency with which such conditions occur;
- evaluate the very large fires of the last 10 years in the context of the historical range of variability using fire occurrence and climatic conditions.

2. Methods

2.1. Study area

Mesa Verde is a high, gently south-dipping cuesta that covers 53,870 ha in southwestern Colorado, USA (Fig. 1). Composed of uplifted and deeply eroded Cretaceous sedimentary rocks, the cuesta rises to a maximum elevation of 2,600 m at the north end, above a steep north-facing escarpment (Griffits, 1990). The main body of the cuesta is composed of broad, gently sloping ridgetops dissected by deep canyons and cliffs. Loess-derived soils are relatively deep and fertile, though very rocky, in the central portions of the broad ridgetops in the northern part of the cuesta, but soils become much shallower and rockier towards the edges of ridgetops and in the southern part of the cuesta (Ramsey, 1999, 2003). MVNP occupies 21,433 ha in the northeastern portion of the cuesta. The remainder of the cuesta lies mostly in the Ute Mountain reservation. The two most extensive vegetation types on the Mesa Verde cuesta are Piñon–Juniper woodlands (*Pinus edulis* and *Juniperus osteosperma*), found mostly in the southern and western portions of the cuesta at slightly lower elevations, and mountain shrublands (also called petran chaparral) dominated by *Q. gambelii* and *Amelanchier utahensis* in the northeastern portion of the cuesta at higher elevations.

Fires are ignited by lightning or humans almost every year, but most are naturally extinguished or suppressed at a very small size. Of the 409 fires recorded in MVNP from 1926 to 1977 (average of 8 fires/year), 90% were <0.1 ha and 8% were 0.1–4 ha in size, but the 2% that exceeded 4 ha accounted for most of the total area burned during that 52-year period (Omi and Emrick, 1980). One reason why most fires are small is that fine fuels tend to be sparse and discontinuous in Mesa Verde's Piñon–Juniper woodlands; large fires usually occur under conditions of very low humidity and fuel moisture (both live and dead) when high winds carry the fire through tree crowns (Omi and Emrick, 1980).

2.2. Data collection

Tree age distributions and stand age estimates: Extensive stand-replacing fires in 2000 burned a variety of Piñon–Juniper stands in MVNP. In 2001 and 2002, we established six 15 m × 15 m plots distributed throughout the burned areas; one additional unburned stand was sampled, as was a clearcut stand that had been recently cleared as a fuel break, for a total of eight sampled stands (Fig. 2). Based on our previous field experience in developing a park vegetation map and other field studies during the previous 10 years, we think that these eight locations represented most of the variability in pre-fire stand structure and environmental conditions within the Piñon–Juniper zone of the park. We collected basal cross-sections from all of the fire-killed Piñon and Juniper trees within each 225 m^2 plot; we collected increment cores from all the Piñon pines in the unburned stand. Piñon sample sizes were as follows: Big Mesa Fire $n = 82$, Lower Chapin $n = 166$, Park Mesa $n = 65$, Wetherill $n = 70$, Waters Canyon $n = 70$, Cedar Tree Tower $n = 70$, Mocassin Mesa $n = 150$, Entrance $n = 45$. Although the 2000 fires consumed much of the litter and dead wood, as well as very small living trees, we observed that they killed but did not consume the larger living saplings and trees (>2.5 cm basal diameter). Therefore, our samples represent a complete census of the stems >2.5 cm in basal diameter that were alive within each plot in 2000. The samples were sanded and cross-dated using standard methods (Stokes and Smiley, 1968). The "Schulman Old" Tree Number one Mesa Verde ITRDD chronology was used to cross-date Piñon pines. Histograms were constructed to show number of stems in each age class, from which we interpreted stand age as described below. The Piñon samples were relatively easy to date, but the Juniper samples could not be cross-dated with confidence, due to false and missing annual rings. Therefore, we used only the Piñon ages from the eight stands to infer disturbance history and stand age in 2000.

Climatic conditions associated with large fires: We obtained monthly precipitation data since 1948 at the Mesa Verde National Park station (05531) from the Western Climate Center (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?comesa), and total area burned each year in MVNP from park records. We performed a correlation and response function analysis using monthly precipitation and a combined winter precipitation variable (previous October through March) by use of the program DendroClim 2002 (written by Franco Biondi, Department of Geography, University of Nevada at Reno), to identify which month(s) had the strongest relationship with burned area. We then conducted a superposed epoch analysis (SEA) to compare climatic conditions, based on these highly correlated months, to fire years, using the program FHX2 (Grissino-Mayer, 2001). SEA uses a window of climatic conditions for years prior to, including, and following, fire years to obtain mean climatic conditions, which are compared to bootstrapped confidence intervals to assess significance.

3. Results

Stand ages as determined from tree age distributions: In all eight stands from which we collected basal

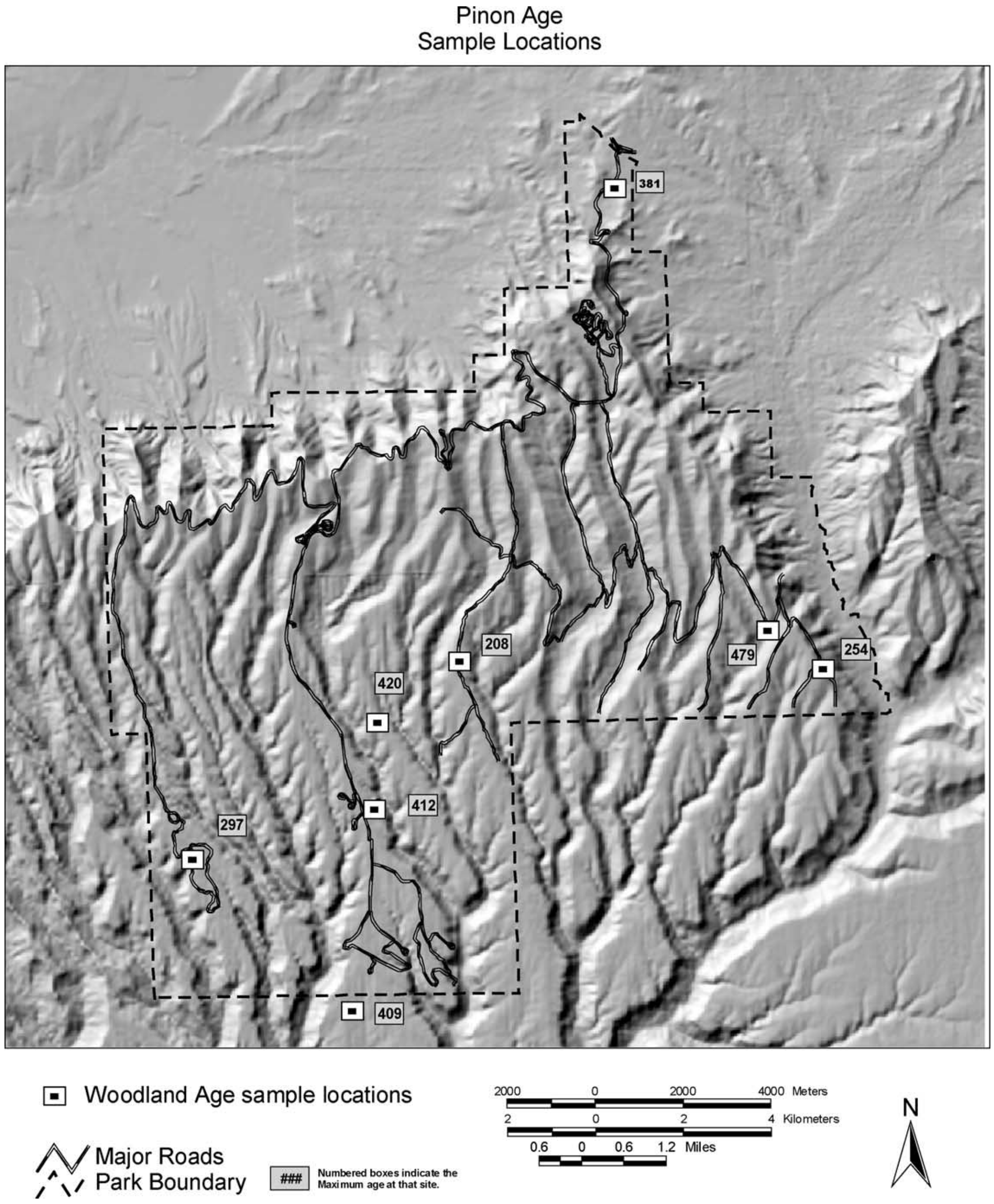
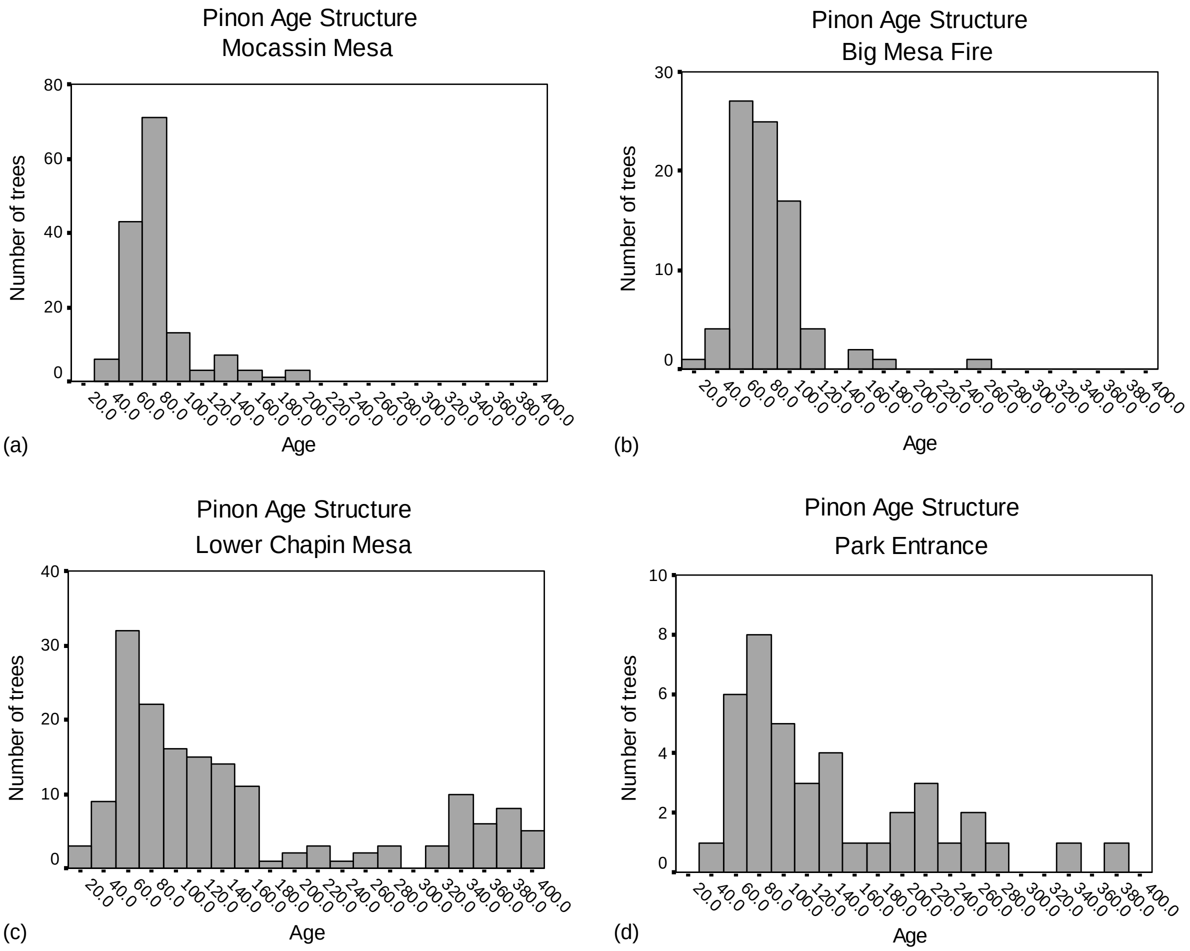


Fig. 2. Locations of eight Piñon–Juniper stands on the Mesa Verde cuesta, Colorado, USA in which stand age was measured.

cross-sections or increment cores, we saw a more-or-less pronounced peak in the 40–140 year age class (Fig. 3). This might be interpreted as a unimodal age structure reflecting a very broadly ‘‘even-aged’’ cohort developing after a disturbance ca. 40–140 years ago (e.g. Whipple and Dix, 1979; Parker and Parker, 1994; Kenkel et al., 1997). However, we think such an explanation is unlikely, for three reasons. First, because we collected only the trees that were not entirely consumed in the 2000 fires, we do not have an adequate sample of the smallest and youngest individuals. The smallest stems in our samples were ca. 2.5 cm in basal diameter, but we know from observations before 2000 that numerous smaller (and presumably younger) stems were present in all of these stands. Therefore, the apparent lack of stems <40 years old in Fig. 3 is at least partially an artifact our sampling method. Secondly, our observations after recent fires in MVNP indicate that Piñon does not typically re-establish as even-aged stands soon after fire (Floyd et al., 2000). On the contrary, Piñon re-establishment following documented 19th and 20th century fires has been extremely slow and gradual. Thirdly, we have good reason to doubt that any of these stands actually had burned ca. 60–120 years ago. We know from park records that none of these areas burned in the 20th century; and other parts of MVNP that we documented to have burned in the mid to late 1800 s are still dominated by mountain shrubland with only scattered trees (Floyd et al., 2000). In contrast, the stands depicted in Fig. 3 were nearly pure Piñon–Juniper in 2000, with only a small shrub component. Therefore, we conclude that the abundance of Piñon trees dating from 1880 to 1940 in Fig. 3 reflects either: (i) a genuine increase in tree density during the last century, as compared with previous centuries, perhaps due to favorable climatic conditions, the lack of fire, or the effects of early 20th century grazing (Harris et al.,


Pinon Age Structure Mocassin Mesa

Pinon Age Structure Big Mesa Fire

Pinon Age Structure Lower Chapin Mesa

Pinon Age Structure Park Entrance

Fig. 3. Piñon age distribution in eight 225 m^2 stands in Mesa Verde National Park, Colorado, USA.

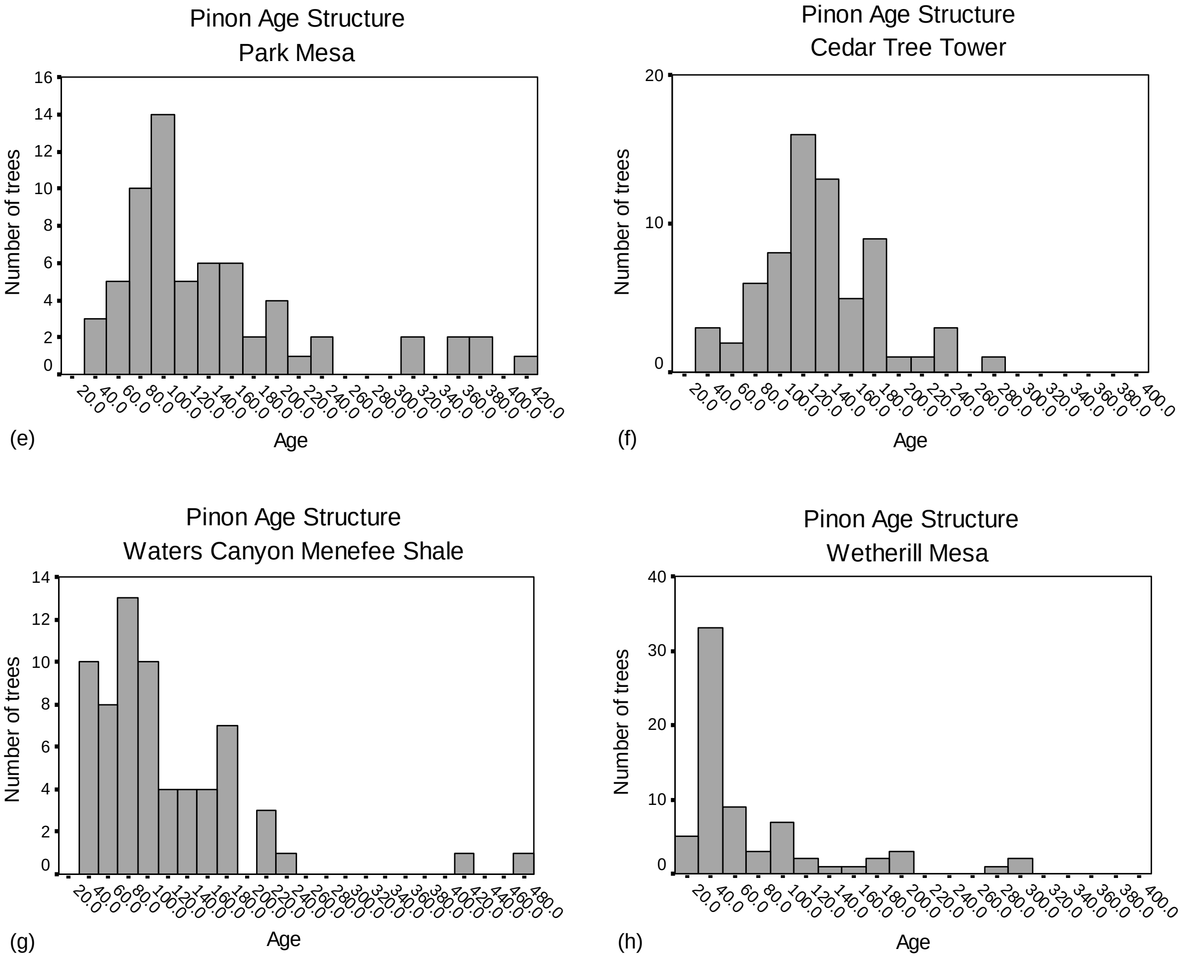


Fig. 3. (*Continued*).

2003; Romme et al., 2003); or (ii) no recent increase in tree density but frequent recruitment compensated by high mortality rates among young to middle-aged tree cohorts due to bark beetles, black-stain root disease, and other causes. Nevertheless, these considerations led us to focus on maximum tree ages, rather than the shape of tree age distribution, in estimating stand age or time since the last stand-replacing fire, as explained below.

Stands dating from 1700 to 1800: Two stands, Big Mesa and Moccasin Mesa, appeared to be 200–300-year-old. The oldest trees were 260 and 200 years, respectively (Fig. 3a and b), and abundant charred Juniper snags were scattered throughout the Big Mesa area prior to the 2000 fires. In a similar-appearing stand on Chapin Mesa, known locally as the ‘‘glades,’’ we had previously determined that the charred Juniper snags dated from a fire in the mid-1700s (Floyd et al., 2000). Total density of Piñon and Juniper in these stands was lower than in stands that lacked charred snags, further supporting our interpretation that these stands are developing after a severe disturbance sometime in the 1700s. We know from fire-scarred ponderosa pine in the foothills of the San Juan Mountains, ca. 100 km north of Mesa Verde, that extensive fires occurred in ponderosa pine forests during several dry years in the 1700s (Grissino-Mayer et al., in press), and major fires may have occurred in the same years in the Piñon–Juniper woodlands of Mesa Verde. However, it is impossible from the data in Fig. 3a and b to determine precisely when the fires occurred in our Big Mesa and Moccasin Mesa stands. Therefore, we concluded simply that the areas represented by these stands in MVNP had last burned between 1700 and 1800 (200–300 years ago).

Stands dating from before 1700: Three stands had an age structure resembling an inverse-J shape: Park Entrance, Park Mesa, and Lower Chapin Mesa (Fig. 3c–e). The oldest trees were 420-year-old, which is near the maximum life span of Piñon on Mesa Verde. As explained above, the apparent lack of very young individuals in Fig. 3c–e was at least partially an artifact of our sampling method that targeted only the larger, older trees not consumed by the 2000 fire. An inverse-J distribution without any old trees is usually associated with a young, expanding population (e.g. He and Duncan, 2000). However, in combination with trees of all age classes, including a very old age class, this type of distribution is thought to represent a quasi-steady-state condition with no strong directional trends in age or density. This type of old-growth stand structure has been described for spruce-fir forest (Leak, 1975; Whipple and Dix, 1979), and appears to characterize these old Piñon–Juniper stands in MVNP. It was impossible from our data to determine exactly when the last stand-replacing disturbance had occurred; it must have been before the oldest extant trees became established. Therefore, we concluded that the areas represented by these stands in MVNP had not burned since 1600 (>400 years old). Some of these areas actually may not have burned since the Ancestral Puebloan occupation of Mesa Verde, which is thought to have involved extensive clearing of the forests prior to abandonment of the area in ca. 1300 AD (Martin and Byers, 1965; Wycoff, 1977; Wagner, 1978).

The age of the remaining three stands was somewhat ambiguous, but all three were likely very old stands. The oldest trees in the Wetherill stand were 300-year-old (Fig. 3f–h). This stand probably was older than the 200–300 year age class described above for the Big Mesa and Mocassin Mesa stands (Fig. 3a and b) because the Wetherill stand was very dense and had no charred Juniper snags before the 2000 fire. It may have originated after a fire 300–350 years ago, or may be an even older quasi-steady-state stand in which the oldest individuals have been removed by bark beetles or other low-severity disturbances. The latter interpretation seems likely, since this stand is close to and structurally similar to another stand on Wetherill Mesa that we previously determined to be >400-year-old (Floyd et al., 2000). The Cedar Tree Tower and Waters Canyon (Fig. 3f–h) stands had a preponderance of trees less than 300-year-old, suggesting that they may have developed after fire around 300 years ago, but they also each contained a single very old tree (420 years). The old trees may have been survivors of a fire ca. 300 years ago, but this seems unlikely since Piñon trees are relatively fire-sensitive. Alternatively, these old individuals may have been the last extant members of the oldest age classes in what are actually quasi-steady-state stands >400-year-old. To be conservative in our interpretations, we simply interpreted these stands as having last burned at some undetermined time prior to 1700 (>300-year-old).

Extent and spatial distribution of age classes in MVNP: In our previous work (Floyd et al., 2000), we produced a time-since-fire map encompassing the major fires that occurred from about 1800 through 1989, based on the ages of post-fire cohorts of re-sprouting Gambel oak (pre-1900 fires) plus 20th century written records (post-1900 fires). All of the stands dating from ca. 1800 or later had a substantial tall mountain shrub component, which we used for dating, but stands lacking shrubs (and apparently originating prior to ca. 1800) could not be dated and were lumped into a single category of ‘‘old’’ stands in this previous work. The present study enabled us to divide this ‘‘old’’ category into two broad age classes (stands originating ca. 1700–1800, represented by two sampled stands, and stands originating earlier than ca 1700, represented by six sampled stands) as described above. We had visited all of these stands before the 2000 fires, in the course of developing a vegetation map for MVNP. We knew from our field notes that both of the stands determined in this present study to date from 1700 to 1800 (based on tree ages) had had a relatively open stand structure and numerous charred Juniper snags prior to the fires in 2000. We had observed a similar open structure and conspicuous charred snags throughout a large area surrounding these two stands in the eastern portion of the cuesta known as Big Mesa. The open canopy structure in this large area also was very apparent in digital orthophoto quadrangles (DOQQ, 1993). In addition, we had previously identified an area in the western portion of MVNP (the ‘‘glades’’) that contained charred snags and had originated after a fire in the mid-1700s, based on tree ages (Floyd et al., 2000). This small area also was conspicuous in digital images. Therefore, we identified all such locations from DOQQ imagery, and mapped them as stands that originated in ca 1700–1800. We had made site visits through most of this area prior to the 2000 fires and verified the presence of charred Juniper snags in the field, so the aerial photo interpretation primarily served to identify exact boundaries of these 200–300-year-old stands.

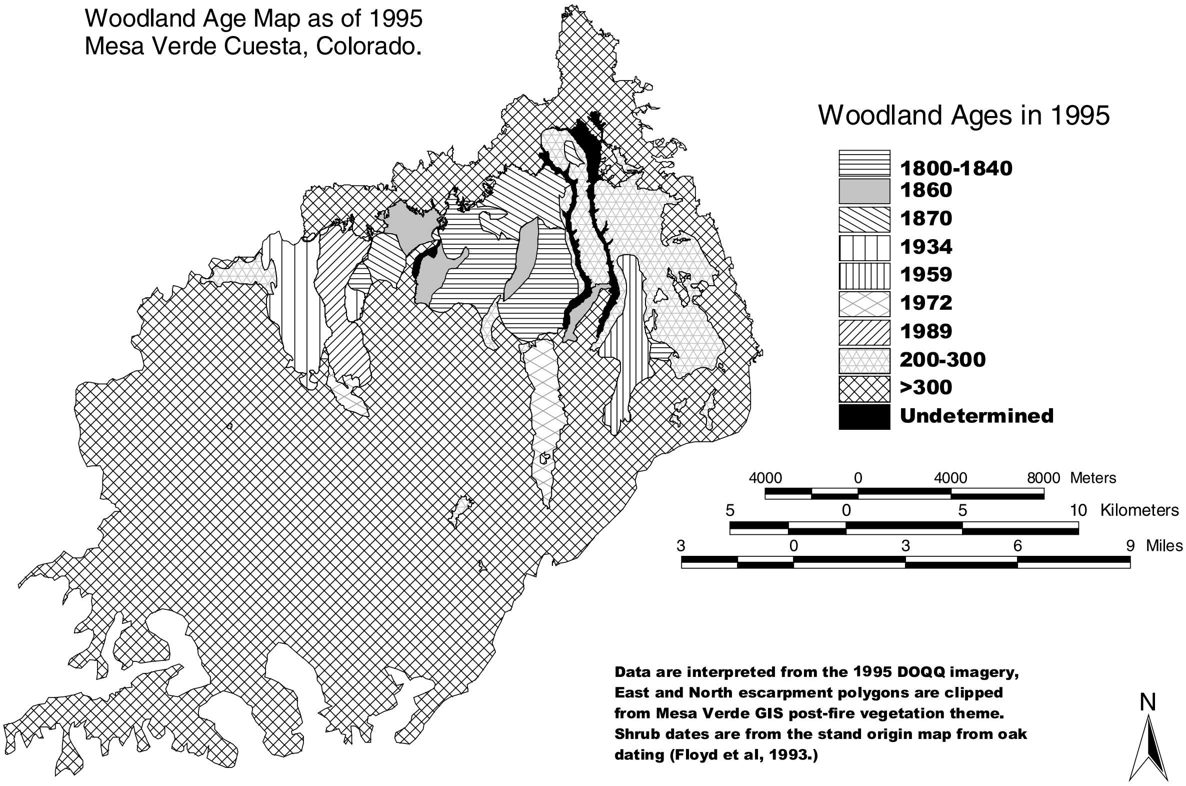
Charred snags or logs had been conspicuously absent prior to 2000 in the six stands whose age structures in this study indicated that they pre-dated 1700. These six stands also were all were relatively dense prior to 2000, and were readily distinguishable on the imagery. Therefore, we mapped all similar stands as older than 300 years, i.e. as having originated at some unknown time before 1700. We assembled all of the above information in a GIS environment to produce a map of stand age (time since the last stand-replacing fire) for all of MVNP (see below).

Interpreting age classes for the entire Mesa Verde cuesta: We had no stand age data for areas outside of MVNP. However, we had observed much of the area in low-altitude over-flights, and had visited a few locations on the ground. Building on our extensive data and interpretations of stand history within the park, we were able to infer fire history and approximate stand ages for areas outside the park, based on aerial imagery encompassing the entire Mesa Verde cuesta. We assumed that areas of shrubland within a matrix of Piñon–Juniper woodland had burned at some time within the last 200 years, as documented in MVNP (Floyd et al., 2000). We assumed that areas of open Piñon–Juniper woodland had burned 200–300 years ago, and that areas of dense Piñon–Juniper woodland had burned >300 years ago (as documented in similar-appearing stands in MVNP in this study). This information also was assembled in the GIS to produce a map of stand age for the entire Mesa Verde cuesta.

1995 stand age map for Mesa Verde: Fig. 4 is the resulting time-since-fire map for MVNP and the Mesa Verde cuesta, as of 1995. The landscape patterns that existed in 1995 are important because they provide a historical context for assessing the large fires of the last decade, as discussed below. The oldest Piñon–Juniper woodlands in 1995 (>300-year-old) were concentrated in the southern and western regions and on the steep escarpments that form the northern and eastern edges of the Mesa Verde cuesta. Piñon–Juniper woodlands of intermediate age (200–300-year-old) were located primarily in the eastern portion of the cuesta, within MVNP. Young woodlands (<200 years old), most of which actually were dominated by Gambel oak and other shrubs, covered much of the top of the cuesta in the northern portion of MVNP.

Table 1 summarizes the areas occupied by Piñon–Juniper woodlands of various ages in MVNP and on the entire Mesa Verde cuesta as of 1995. In 1995, 11% of MVNP and 9% of the entire cuesta were covered by shrub-dominated stands that originated after fires during the 20th century; 26 and 10%, respectively, were older shrublands with scattered Piñon and Juniper trees, dating from fires in the 19th century; 15 and 7% were open Piñon–Juniper woodlands dating from fires in the 18th century; and 45 and 74%, respectively, were old Piñon–Juniper woodlands that had not burned since 1700.

Climatic conditions associated with large fires: Lightning or human ignited fires occurred in MVNP in almost every year from 1949 to 2002 (Omi and Emrick, 1980, and park records). However, large fires (>100 ha) only occurred in 6 years: 1959, 1972, 1989, 1996, 2000, and 2002 (Fig. 5). Another large fire occurred in 2003, but 2003 was deleted from the analysis because of incomplete climate data for this year. The two climatic variables most strongly correlated in a Superposed Epoch analysis with large fire years in MVNP from 1949 to 2002 were total precipitation during the previous winter (October–March) and total May precipitation. Years with large fires were associated with significantly low precipitation during the previous winter, i.e. lying below the 99% confidence interval for winter precipitation during all years between 1949 and 2002 (Fig. 6). Mean total winter precipitation in fire years was only 14.8 cm compared with a 27.3 mean for all years 1949–2002. Years with large fires also were associated with significantly low May precipitation, i.e. lying below the 95% confidence interval for all years between 1949 and 2002 (Fig. 7). Mean May precipitation in fire years was only 0.2 cm, compared with a 2.7 cm mean for all years 1949–2002.



Data are interpreted from the 1995 DOQQ imagery, East and North escarpment polygons are clipped from Mesa Verde GIS post-fire vegetation theme. Shrub dates are from the stand origin map from oak dating (Floyd et al, 1993.)

Fig. 4. Stand age (time since last stand-replacing fire) in Mesa Verde National Park and on the Mesa Verde cuesta, Colorado, USA, as of 1995.

Table 1
Area covered by stands of various ages (time since last stand-replacing fire) in Mesa Verde National Park (MVNP), and on the entire Mesa Verde cuesta, Colorado, USA, as of 1995

Age class (years)	Date of last stand-replacing fire	Hectares in MVNP	Area of MVNP (%)	Hectares on Mesa Verde cuesta	Area of Mesa Verde cuesta (%)
6	1989	1005	5	1005	2
23	1972	439	2	917	2
36	1959	528	2	858	2
61	1934	493	2	1386	3
0–90	1900–1989	2465	11	4166	9
ca. 120	1870s	1154	5	1167	2
ca. 130	1860s	1010	5	1010	2
150–200	1800–1850	3451	16	3461	6
100–200	1800–1900	5615	26	5638	10
200–300	1700–1800	3185	15	3687	7
>300	Pre–1700	9640	45	39851	74
	Unknown	527	2	527	1
Total	–	21433	100	53870	100

Also see Fig. 2. No major fires occurred from 1880 to 1934 (Floyd et al., 2000). Note that extensive fires in 1996, 2000, 2002, and 2003 burned 15,663 ha, burning over the areas affected by earlier fires, and creating a new mosaic of stand ages (see Table 3, Fig. 4).

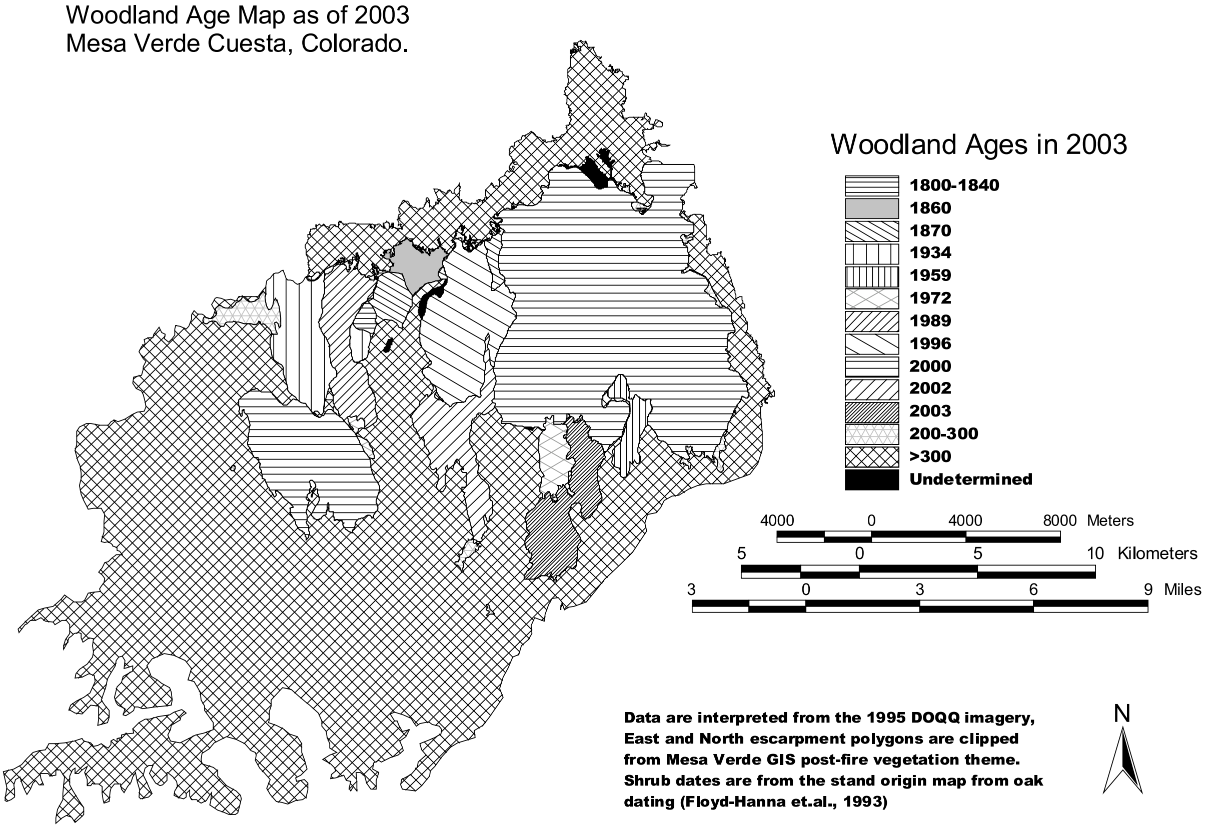


Fig. 5. Stand age (time since last stand-replacing fire) in Mesa Verde National Park, Colorado, USA as of 2003.

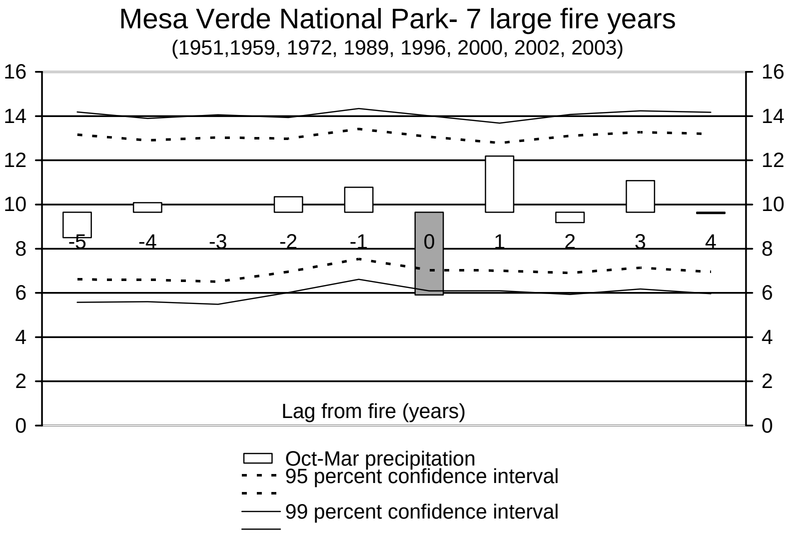


Fig. 6. Superposed epoch analysis for large fires and total previous winter precipitation (October–March, inches) in Mesa Verde National Park, Colorado, USA.

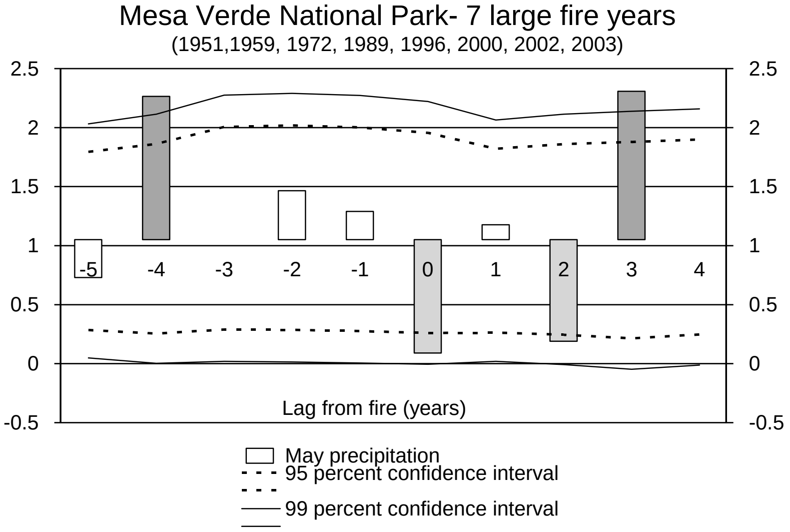


Fig. 7. Superposed epoch analysis for large fires and total May precipitation (inches) in Mesa Verde National Park, Colorado, USA.

4. Discussion

Reconstructing prehistoric fire history in Piñon–Juniper woodlands of western North America is methodologically challenging, because fire scars tend to be rare and Piñon and Juniper tend to re-establish only slowly and gradually after fire (Baker and Shinneman, 2004). Nevertheless, we were able to identify four broad age classes of Piñon–Juniper woodland by combining several kinds of information (Table 2). The two older age classes that we have identified are very broad, but even such broad characterization of stand ages in mature Piñon–Juniper vegetation was previously unavailable. We suggest that this general approach for estimating stand age in Piñon–Juniper woodlands is applicable to many other areas in the Southwest, where stand ages currently are unknown.

Our findings indicate that large fires have occurred previously in the Piñon–Juniper woodlands of Mesa Verde (Table 1, Fig. 3). From data of this kind, it is possible to estimate the fire rotation, i.e. the time required to burn an area equal to the size of the entire study area (Baker and Ehle, 2001). A commonly used approach is to fit empirical time-since-fire data to a statistical model such as the Weibull distribution, from which rotation time can be determined from the

Table 2
Stand age classes in Piñon–Juniper forests and criteria for recognizing them in Mesa Verde National Park, Colorado, USA

Stands <100-year-old are documented by park maps and written fire records. Precise fire years are known for these areas. Currently these stands are dominated by shrubs and herbs (e.g. *Quercus gambelii, Amelanchier utahensis, Poa fendleriana*, and *Penstemon lineariodes*), with few or no trees
Stands 100–200-year-old (burned in the 19th century) are documented by post-fire cohorts of Gambel oak (Floyd et al., 2000). Fire years are known within about a decade. Currently, these stands are dominated by shrubs (e.g. *Quercus gambelii*, and *Amelanchier utahensis*), with scattered Piñon and Juniper trees
Stands 200–300-year-old (burned in 18th century) are documented by low tree densities, numerous charred Juniper snags, and maximum tree ages of 200–300 years. Fire years are not known, except that they were sometime within the 18th century. Currently, these stands are open woodlands of Piñon and Juniper
Stands >300-year-old (burned prior to 1700) are documented by high tree densities, absence or paucity of charred snags or logs, and at least some individual Piñon trees >300-year-old. Fire years are unknown, and some or all of these areas may not have burned since the Ancestral Puebloan people abandoned Mesa Verde around 1300 AD. Currently these stands are very dense Piñon–Juniper forests (Floyd, 2003)

parameters of the model (Johnson and Gutsell, 1994). Unfortunately, as we found previously (Floyd et al., 2000), our empirical time-since-fire data from Mesa Verde did not fit the Weibull or any other standard statistical distribution because of the large proportion of stands that had no evidence of fire. Therefore, as in Floyd et al. (2000), we used simple statistical reasoning to arrive at a very approximate but nevertheless useful estimate of the fire rotation in the Piñon–Juniper woodlands of Mesa Verde.

Historical fire rotations in Piñon–Juniper woodlands of Mesa Verde: We see from Table 1 that, in 1995, 41% of the area in MVNP dated from fires between 1700 and 1900. If some of the areas burned in the early 1700s were re-burned later in the 1700s or 1800s (almost certainly true), then the total area burned during this 200-year period probably was approximately half the total area of the park. By this reasoning, the rotation for MVNP would be about two times 200 years or approximately 400 years. Note that we also obtained a 400-year estimate of fire rotation in our previous work, based on the extent of burning of Piñon–Juniper woodland during the second half of the 20th century (Floyd et al., 2000). This convergence of fire rotation estimates derived from areas burned from 1700 to 1900 (this study) and from 1940 to 1990 (Floyd et al., 2000) suggests that the ca. 400-years estimate is fairly robust, and also supports our earlier interpretation that 20th-century fire suppression did not fundamentally alter the fire regime in MVNP (Floyd et al., 2000).

Our previous analysis (Floyd et al., 2000) was restricted to MVNP per se, but the data in Table 1 also can be used to estimate fire rotation for the entire Mesa Verde cuesta. The cuesta as a whole contains a much greater proportion of old woodland (unburned since 1700 AD) than does MVNP; indeed, only 17% of the cuesta area dates from fires between 1700 and 1900 (Table 1). It is nearly impossible to directly calculate rotation time from this information. However, the 17% of the cuesta that dates from 1700 to 1900 is approximately half the area in MVNP that dates from this same 200-year period. If the proportion of the cuesta that burns in any given period is only half the proportion within the smaller area of MVNP that burns within that time period, then the rotation time for the cuesta may be roughly twice as long as for MVNP. By this reasoning, the rotation time for the cuesta as a whole may be centuries longer, although the absolute numerical value of this estimate is questionable.

Two important patterns are apparent. First, the fire rotation for the entire cuesta appears substantially longer than the rotation for that portion of the cuesta that lies within MVNP, i.e. large fires historically have been more frequent in the park area than on the cuesta as a whole. Although we cannot rule out the possibility that the fire rotation actually is similar throughout the cuesta and by chance the northeastern corner has burned more frequently than other portions, we can identify two reasons why the area occupied by MVNP in fact might be expected to have a shorter fire rotation. The first reason has to do with spatial patterns in soil characteristics (Ramsey, 2003): generally shallower soils in the southern part of the cuesta (mostly outside of the park) may support lower productivity which leads to reduced fuel continuity and a lower probability of extensive fires, relative to areas having generally deeper soils in the northern part of the cuesta where MVNP is located (Romme et al., 2003). The second reason is related to the park's location at relatively higher elevations in the northeastern portion of the cuesta (Fig. 1). Given the prevailing southwesterly winds of this region, fires igniting almost anywhere on the cuesta could potentially spread into this northeastern corner, whereas the southern and western portions of the cuesta would be likely to burn only if ignitions occurred locally (Floyd et al., 2000). The second major pattern that is apparent from our reconstructions of fire history is that the historical fire rotations both within the park (ca. 400 years) and on the entire cuesta (substantially greater than 400 years) were far longer than is commonly assumed for Piñon–Juniper vegetation (Schmidt et al., 2002; Baker and Shinneman, 2004). Further, our data do not support the fire regime condition classes that have been assigned to this area (Schmidt et al., 2002). On Mesa Verde, and perhaps much of the Colorado Plateau, the historical fire regime of Piñon–Juniper vegetation was characterized by infrequent but high-severity fires—more similar to high-elevation forests (e.g. spruce-fir) than to lower-elevation ponderosa pine forests (Romme et al., 2003).

Assessing recent large fires in Mesa Verde: The landscape mosaic that existed in 1995 (Fig. 3) provided insights into prehistoric fire patterns. However, the 1995 landscape mosaic has been largely obliterated by a series of very large fires in 1996, 2000, 2002, and 2003 (Fig. 8). The fires of the last decade in MVNP and surrounding portions of the Mesa Verde cuesta have burned a total of 15,663 ha—more than three times the total area burned in the previous century (Table 3). It is important to recognize that these recent fires have not been more severe than previous fires, because all of the large fires of the 20th century and prior to 1900 were predominantly stand-replacing, just like the fires since 1995. Nevertheless, the frequency of large, severe fires during the last 10 years clearly exceeds anything observed in the previous 100 years. In fact, the 15,663 ha that burned from 1996 to 2003 appears to be 10 times greater than the area burned in any previous decade of the last 150

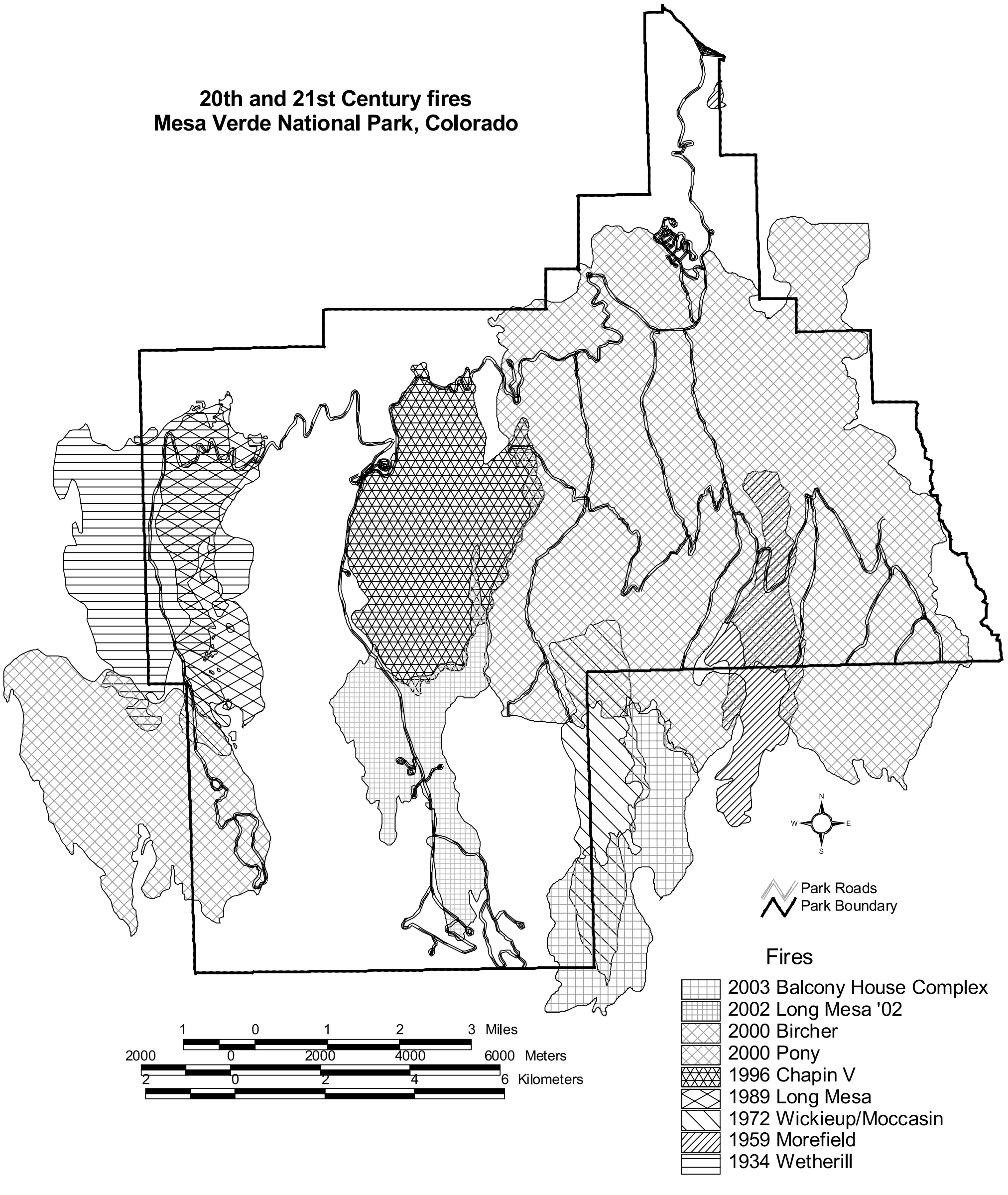


Fig. 8. Large fires since 1934 on the Mesa Verde cuesta, Colorado, USA.

Table 3
Actual fire sizes during the last century, as documented by written records, and estimated minimum fire sizes in previous centuries as reconstructed from tree ages, on the Mesa Verde cuesta

Fire years	Hectares on Mesa Verde cuesta	Area of Mesa Verde cuesta (%)
2003	1127	2
2002	1067	2
2000	11535	21
1996	1935	4
Total: 1996–2003	15663	29
1989	1000	2
1972	1106	2
1959	854	2
1934	1895	4
Total: 1900–1995	4855	9
1870s	1167	2
1860s	1010	2
1800–1850	3461	6
Total: 1800–1900	5638	10
Total: 1700–1800	3687	7

Note that the numbers in this table depict total extent of each fire from 1934 to 2003, including re-burning of some areas that had burned previously. Thus, some of these numbers are larger than the numbers in Table 1, which subtracts from the extent of earlier fires the areas burned in later fires. Extents of pre-1900 fires in this table are taken directly from Table 1, however, and therefore represent minimum extents of prehistoric fires.

years, either in MVNP or on the Mesa Verde cuesta as a whole (Table 3). Moreover, the total area burned in the last 7 years may be greater even than the total area burned in any century since 1600—although the total area burned in the 17th century may have been much larger than our numbers indicate because of subsequent re-burning (Table 4).

We return now to the two possible interpretations of recent fires in Mesa Verde that were raised in the introduction: (i) that they were similar in frequency and extent to fires in previous decades during the last 400 years when similarly dry climatic conditions prevailed, i.e. that recent fire activity has been within the historical range of variability for this ecosystem; or (ii) that recent fire activity in Mesa Verde is unprecedented in the last 400 years, even during previous dry periods, and thus represents a significant departure from the historical range of variability We cannot definitively support or refute either interpretation, but our historical data do inform the debate. Although the extent of burning in the last decade does appear unprecedented within the past 400 years (especially within MVNP, but also on the cuesta as a whole), this does not necessarily mean that recent fire activity is outside the historical range of variability. In ecosystems characterized by infrequent, high-severity fires at long intervals, we should expect to see long periods without substantial fire, punctuated by extensive burning during short periods of dry climatic conditions. In this respect, Mesa Verde appears similar to the Yellowstone system (Romme and Despain, 1989).

On the other hand, if we interpret recent fires as being outside the historical fire regime, we must identify the mechanisms that would explain such a dramatic change. Two possible explanations are that: (i) the last decade has been characterized by unusually frequent climatic conditions conducive to large fires (the “drought hypothesis”); or (ii) stand structure (e.g. tree density and fuel conditions) has changed in ways that make today’s woodlands more susceptible to severe fire than previously (the “fuel hypothesis”) (Table 4).

The drought hypothesis is partially supported by the results of superposed epoch analysis. Large fire years in MVNP are associated with significantly low precipitation in the preceding winter and in the month of May (Figs. 6 and 7). These climatic conditions have occurred in three of the past 7 years, and in each of those years a large fire occurred (Table 5). However, when comparing the frequency of these significantly dry years in the past 7 years with previous 7-year periods since 1949 (Table 5), it is apparent that frequencies of dry climatic conditions were as great or nearly as great during the period 1968–1981 as they were from 1996 to 2002. Nevertheless, there was only one large fire, in 1972, during the period 1968–1981. Fire suppression capabilities were no more effective in the 1960s and 1970s than they are today; on the contrary, they probably were less effective. Yet Mesa Verde had fewer large fires during that earlier period when climatic conditions were nearly as suitable for large fires as they have been in the last 7 years. Therefore, although the extreme drought of the last 7 years clearly is an important part of the explanation for the extensive fires since 1996 in Mesa Verde, it cannot be the entire explanation.

It is not possible to directly test the fuels hypothesis with our data, but we can bring to bear some pertinent

Table 4
Area covered by stands of various ages (time since last stand-replacing fire) in Mesa Verde National Park (MVNP), and on the entire Mesa Verde cuesta, Colorado, USA, as of 2003

Age class (years)	Date of last stand-replacing fire	Hectares in MVNP	Area of MVNP (%)	Hectares on Mesa Verde cuesta	Area of Mesa Verde cuesta (%)
0	2003	215	1	1105	2
1	2002	1067	5	1067	2
3	2000	8344	39	11506	21
7	1996	1764	8	1764	3
0–7	1996–2003	11390	53	15442	28
14	1989	1002	5	1002	2
31	1972	153	1	417	<1
44	1959	70	<1	348	<1
69	1934	447	2	1279	2
14–69	1934–1989	1672	8	3046	6
ca. 120	1870s	383	2	388	<1
ca. 130	1860s	373	2	373	<1
150–200	1800–1850	1096	5	1096	2
100–200	1800–1900	1852	9	1857	3
200–300	1700–1800	103	<1	446	1
>300	Pre-1700	6314	29	32976	61
	Unknown	103	<1	103	<1
Total	–	21433	100	53870	100

Compare with Table 1 which shows similar data for 1995, just prior to the extensive fires of the last 7 years.

observations. First, our stand age data show that there was substantial tree establishment throughout the 20th century (Fig. 3). Because we lack data on tree mortality rates, we cannot determine whether these patterns represent a genuine increase in stand densities compared with the 19th century. Old photos of MVNP (Romme et al., 2003) show that many early 1900's stands were relatively dense, but the oblique angle of the old photos precludes any quantitative measurement of stand densities, and densities may

Table 5
Occurrence of dry winters (October–March), dry Mays, and large fires (>100 ha) in Mesa Verde National Park from 1949 to 2002

Years	Number of years with significantly low winter precipitation	Number of years with significantly low May precipitation	Number of years in which both winter and May precipitation were significantly low	Number of large fires (>100 ha)	Time elapsed since the last large fire
1949–1953	2 (1951, 1953)	2 (1952, 1953)	1 (1953)	0	–
1954–1960	1 (1959)	1 (1959)	1 (1959)	1 (1959)	25 years[a]
1961–1967	0	2 (1961, 1963)	0	0	–
1968–1974	3 (1971, 1972, 1974)	4 (1969, 1970, 1972)	2 (1972, 1974)	1 (1972)	13 years
1975–1981	3 (1976, 1977, 1981	1 1977)	1 (1977)	0	–
1982–1988	0	0	0	0	–
1989–1995	1 (1990)	2 (1989, 1991)	0	1 (1989)	17 years
1996–2002	3 (1996, 2000, 2002)	4 (1996, 1998, 2000, 2002)	3 (1996, 2000, 2002)	3 (1996, 2000, 2002)	7 years, 4 years, 2 years

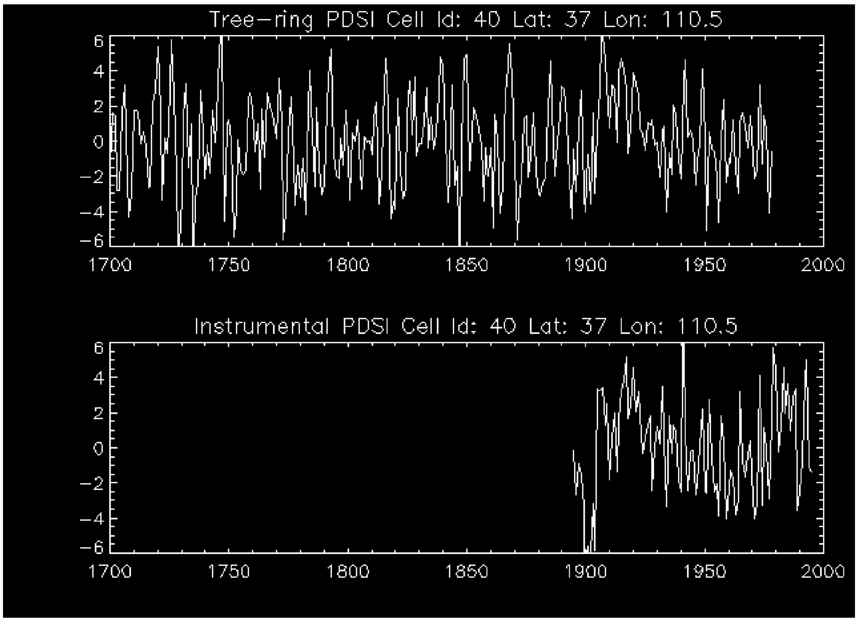
Large fires are associated with significantly low precipitation (at or below the lower 95% confidence interval for mean precipitation) in the preceding winter and in May (Figs. 8 and 9). However, large fires do not occur in all dry years because of variability in ignition and other stochastic processes.

[a] A large fire occurred in Mesa Verde National Park and surrounding Ute lands in 1934 (see Table 3).

have become even greater during the last 100 years. This interpretation is made more plausible by the fact that overall climatic conditions of the 20th century were conducive to tree establishment throughout the Southwest (e.g. Covington and Moore, 1994; Grissino-Mayer, 1995), and that 20th century increases in Piñon and Juniper densities have been documented elsewhere in the West (e.g. Miller and Wigand, 1994; Miller and Tausch, 2001). Reconstructions of the Palmer Drought Severity Index (PDSI) for two stations located near Mesa Verde also show that the early 20th century, as well as the period from about 1980 to 1995, were unusually wet in comparison with previous centuries (Fig. 9). It is possible that a process of slowly increasing tree densities during the last 100 years has gradually increased the mass and continuity of canopy fuels in Piñon–Juniper woodlands of Mesa Verde and other similar places, and is resulting in a progressive increase in the frequency of large, wind-driven fires whenever extremely dry climatic conditions occur— as they have in the last decade in Mesa Verde. We note, however, that similar increases in stand density have occurred in other Piñon–Juniper systems in western Colorado, e.g. the Uncompahgre Plateau ca. 200 km north of Mesa Verde (Eisenhart, 2003, Baker, personal communication), but these other areas have not experienced the dramatic increase in large fires that we have seen in Mesa Verde.

Management implications: Our data support the interpretation that low-severity, stand-thinning fires were never an important component of this system; rather, the fire regime has always been dominated by infrequent stand-replacing fires (Romme et al., 2003). This is in marked contrast to the fire regime condition classes proposed by Schmidt et al. (2002) for this region, a discrepancy that is critical to management decisions that are informed by natural fire regimes. Moreover, the changes that we suggest in stand structure and fuel characteristics apparently are being driven by normal tree responses to prolonged periods of favorable moisture conditions during the last 100 years. In other words, this pattern of canopy fuel build-up during wet, fire-free decades, followed by stand-replacing fire during subsequent droughts, likely represents the natural condition for Mesa Verde. Thus, the frequency of large fires during the last decade does not necessarily imply any fundamental change in the natural fire regime, but simply may reflect a pattern that would be expected in an ecosystem having a centuries-long fire rotation. We see no strong ecological justification for extensive mechanical fuel reduction or low-severity prescribed fire to "restore" prehistoric stand structure, especially where the goal is maintenance of natural ecological conditions, because the post-1900 changes in stand structure and fire activity have been a mostly "natural" response to the climate of the 20th and early 21st centuries. On the other hand, our findings do support the idea of fuel reduction in the vicinity of fire-sensitive cultural resources (e.g. buildings and archaeological sites), because fire hazards in untreated Piñon–Juniper woodlands are indeed high and perhaps increasing with time.

In sum, we have reconstructed the historical fire regime and associated landscape mosaics of woodland age classes in the Piñon–Juniper woodlands of Mesa Verde during the last 300 years. This information has provided an appropriate historical context for evaluating the large severe fires of the last decade. We conclude that the recent spate of large fires in Piñon–Juniper woodlands of Mesa Verde and elsewhere in the Southwest probably is the natural consequence of: (i) the generally moist 20th century climate, which allowed tree densities and canopy fuel continuities to gradually increase; and (ii) the current severe, regional drought that is providing the dry conditions necessary for extensive burning. Large severe fires have occurred many times in the past in Mesa Verde, but the frequency and extent of severe fires in the last 10 years appears unprecedented in the previous 300 years. We apparently are witnessing a unique period in the ecological history of the southwest, a period when vegetation patterns are being altered over extensive areas within a very short time. If the current drought continues, we ultimately may lose much of the old-growth Piñon Juniper woodland in the southwest. A major concern is that aggressive, non-native species will invade much of the burned area, with unknown but potentially serious ecological consequences (D'Antonio, 2000). There may be little that land managers can do to prevent this transformation of the Piñon–Juniper landscape, aside from taking local actions to protect fire-sensitive structures and other resources, and to retard the spread of invasive plants.



Station 50

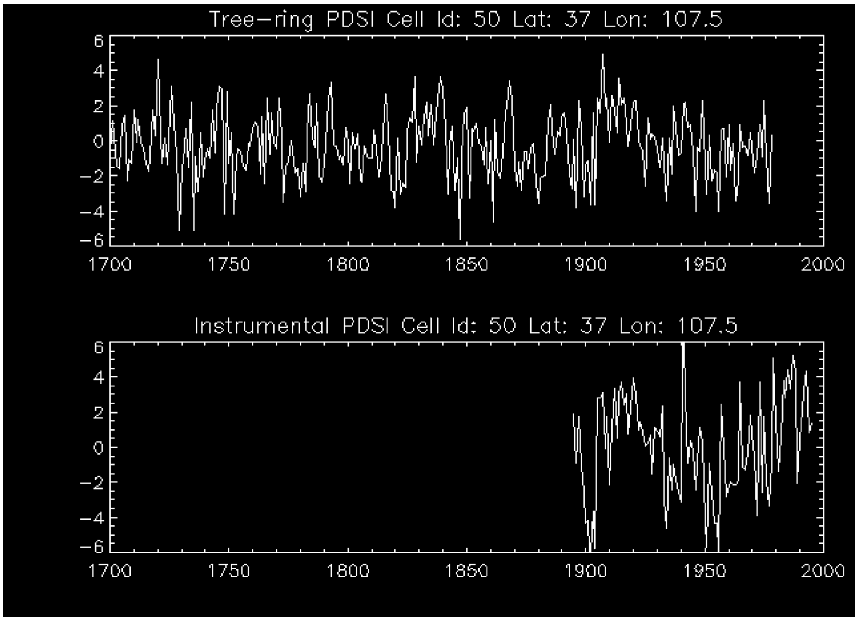


Fig. 9. Palmer drought severity indices for stations 40 and 50, located near Mesa Verde National Park, Colorado (data from: http://www.ngdc.noaa.gov/paleo/usclient2.html).

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