Using tree recruitment patterns and fire history to guide restoration of an unlogged ponderosa pine/Douglas-fir landscape in the southern Rocky Mountains after a century of fire suppression

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Summary

Tree age and fire history were studied in an unlogged ponderosa pine/Douglas-fir (*Pinus ponderosa*/*Pseudotsuga menziesii*) landscape in the Colorado Front Range mountains. These data were analysed to understand tree survival during fire and post-fire recruitment patterns after fire, as a basis for understanding the characteristics of, and restoration needs for, an ecologically sustainable landscape. Comparisons of two independent tree age data sets indicated that sampling what subjectively appear to be the five oldest trees in a forest polygon could identify the oldest tree. Comparisons of the ages of the oldest trees in each data set with maps of fire history suggested that delays in establishment of trees, after stand-replacing fire, ranged from a few years to more than a century. These data indicate that variable fire severity, including patches of stand replacement, and variable temporal patterns of tree recruitment into openings after fire were major causes of spatial heterogeneity of patch structure in the landscape. These effects suggest that restoring current dense and homogeneous ponderosa pine forests to an ecologically sustainable and dynamic condition should reflect the roles of fires and variable patterns of tree recruitment in regulating landscape structure.

Introduction

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) forests are extensive in the western US, and fire historically played a significant role in shaping forest structure across the landscape. However, logging, livestock grazing, fire suppression and urban encroachment are major human influences that altered forests from their condition when Euro-American settlers arrived. Many current ponderosa pine stands are dense and young, with excessive fuels that support unusually severe fire for this species. In recent decades, vast areas have become especially vulnerable to severe and large crown fires and widespread insect epidemics. Ponderosa pine forest restoration is needed in many places in the western US to return forests to an ecologically sustainable condition and reduce the hazard of catastrophic crown fires and insect epidemics.

Ponderosa pine forests differ from other higher elevation coniferous forests or forests at more northerly latitudes. Ponderosa pine trees are adapted to survive periodic low-intensity fires. They have thick bark, few limbs near the ground and fairly sparse, lengthy needles that protect buds. Historically, surface fires often burned beneath ponderosa pine trees with only limited scorching of the crown. Most ponderosa pine stands are uneven-aged. In contrast, lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and other subalpine or boreal tree species are sensitive to fire and usually do not survive fire events. Lodgepole pine also depends on fire, however. Fires generally occur as crown fires in older stands during drought years, killing trees over large areas. New even-aged forests are established from seeds released from cones that survive fire.

Protection from undesirable impacts of large crown fires in current ponderosa pine forests may be achieved by thinning forests to limit the intensity and spread of fire. The study of historically intact forest landscapes would provide much needed insight into the structure and regulating processes of sustainable forest ecosystems. However, achieving sustainable ecological conditions and conserving biodiversity for this forest type may require specific guidelines that reflect differences in historical characteristics of these forests depending on their location. Historical fire behaviour in ponderosa pine forests in the southwestern US, for example, was dominated by low-intensity surface fires that maintained an open forest structure and grassy understorey (Covington and Moore, 1994). In contrast, a mixed severity fire behaviour pattern having both a stand-replacing component and surface fire component dominated ponderosa pine forests in the Colorado Front Range (Brown *et al.*, 1999; Kaufmann *et al.*, 2001).

Only limited research has been done on the structure of ponderosa pine forests prior to human impact, and almost none has been done at a landscape scale (but see Fulé *et al.*, 1997). Furthermore, few areas in an undisturbed condition are available to study the structure, composition, and processes that characterized historical landscapes. A notable exception was a 35-km^2 ponderosa pine/Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) landscape at Cheesman Lake in the Colorado Front Range of the southern Rocky Mountains. This landscape has since been severely burned (see below), but considerable research had already been completed (e.g. Brown *et al.*, 1999; Kaufmann *et al.*, 2000a, b, 2001; Huckaby *et al.*, 2001). Fire suppression during the last century resulted in ingrowth of younger trees, but the lack of logging made this forested landscape an exceptional site for studying historical landscape features because fire scars were readily available and the pre-settlement tree age structure was mostly intact. While Native Americans were present in Colorado Front Range forests, it is believed that their influence on forest structure in the Cheesman Lake landscape was limited. Sparse understorey vegetation probably limited the spread of fire in these coarse soils, and lightning may have been as effective an ignition source as humans when fuels were adequate. Restoration had begun in this landscape to offset the effects of fire suppression during the last century. Restoration also has begun on adjacent lands affected by logging, grazing and fire suppression, including treatment on 5000 ha in the Upper South Platte Restoration Project (Kaufmann and Hessel, 2000). In these and similar areas in the Colorado Front Range and elsewhere, knowledge of historical landscape structure is required to assure that forest restoration achieves the desired outcomes of ecological sustainability and wildfire risk reduction.

The historical features of the Cheesman Lake landscape have been lost. The 55 000 ha Hayman fire that began under severe drought conditions on 8 June 2002 burned the Cheesman Lake landscape and surrounding areas. The study landscape was in the centre of an area of about 18 000–20 000 ha that burned at high severity on 9 June, with the fire travelling ~30 km through dense, dry forest in 1 day. All of the Cheesman Lake landscape burned, with complete tree mortality on ~95 per cent of the landscape. Tree age data indicate that the size of area burned with complete mortality was unprecedented over the last five centuries (Huckaby *et al.*, 2001). The restoration that had been planned for the landscape is now impossible. Nonetheless, the lessons learned from Cheesman are still appropriate for extensive adjacent areas badly in need of restoration to reduce the probabilities of such a fire occurring elsewhere.

Our research provides considerable information about the historical Cheesman Lake landscape, including an eighth-century fire history. Before fire suppression and long before the recent devastating fire, the landscape was characterized by low-density forests and openings created by fires (Brown *et al.*, 1999; Kaufmann *et al.*, 2001). Between 1500 and 1900, seven large fires with a mean fire interval of 50 years appear to have had a major influence on forest structure at a landscape scale (35 km^2). Nearly all of these fires scarred trees at multiple times of the year, indicating a long burning season. A number of small fires occurred also, though age data presented below and other data that are unpublished indicate that such fires probably had a limited effect on overstorey structure. Prior to fire suppression during the twentieth century, fire-resistant ponderosa pine forests dominated all but the north aspects, where about half the tree density was Douglas-fir, a fire-sensitive species (Kaufmann *et al.*, 2000b). Maps of fire scars indicated that fires at Cheesman Lake were often larger than 5 km^2 and were mixed in severity (Huckaby *et al.*, 2001). Both surface and localized crown fires maintained a complex and dynamic landscape mosaic of low-density forest patches and transient openings from <1 to >100 ha in size (Brown *et al.*, 1999; Kaufmann *et al.*, 2001). The openings contained shrubs and herbs typically associated with forest habitats, but lacked a tree canopy, apparently because of fire-caused mortality followed by very slow reforestation. Tree age studies indicated that past fires often were followed by tree recruitment pulses lasting up to 10 years, but sometimes not occurring until several decades or more after the fire (Kaufmann *et al.*, 2000a). Thus transient openings were a prominent feature of the historical landscape (Kaufmann *et al.*, 2001).

In this paper, we assess how fire history and tree age data for the Cheesman Lake landscape can be used to develop forest restoration guidelines that reflect historical spatial and temporal heterogeneity at a landscape scale. Previous publications on Cheesman Lake reported on overall landscape structure and processes but did not assess specifically how tree age structure and fire history could be used together to assess historical landscape dynamics. We focus on a portion of the Cheesman Lake landscape where we have excellent fire history data and two independently derived tree age data sets. We use maps of past fires for the landscape and tree ages in sample plots and polygons to assess specifically how differences in fire severity and delays in tree recruitment after fires contributed to spatial heterogeneity of patch structure in the landscape. This will allow a temporal and spatial assessment of the historical patch structure for the entire Cheesman Lake landscape, which will facilitate the development of specific restoration guidelines for surrounding areas influenced by human activities and at risk of large-scale crown fire.

Methods

The Cheesman Lake ponderosa pine/Douglas-fir landscape surrounds a reservoir on the South Platte River south-west of Denver, CO, USA. The 35-km^2 landscape, owned by the Denver Water Department, is in rolling to steep topography at 2000–2500 m elevation, near the middle of the elevational zone for this forest type in the Colorado Front Range. It was unlogged, and it had been protected from livestock grazing since 1905, when dam construction was completed to create the reservoir. Forest polygons of homogeneous canopy cover and tree size distribution were mapped for the landscape using colour infrared photographs (1 : 6000 scale) taken in 1996, and polygons were classified with a photo interpretation template for canopy cover (Huckaby *et al.*, 2001; Kaufmann *et al.*, 2001). Polygon areas varied from <0.2 to >35 ha.

In this paper we focus on a 4-km^2 area in the south-east corner of the Cheesman Lake landscape. Locations of fire scar samples are shown in Figure 1a (Brown *et al.*, 1999). Fire history data indicated that of the seven large fires in the

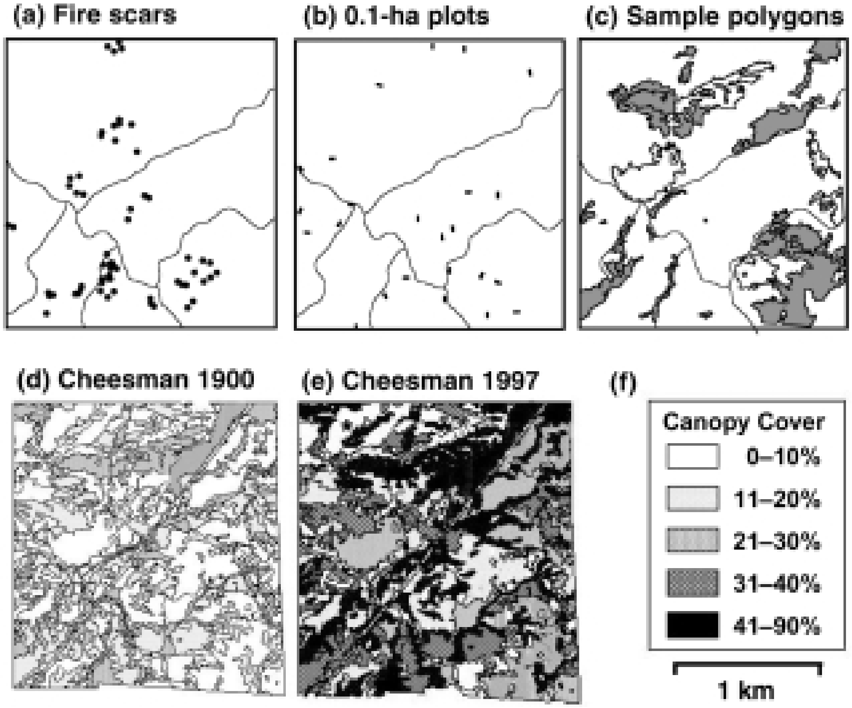

Figure 1. Maps of 4-km^2 study area at Cheesman Lake, Colorado, USA: (a) fire scar locations and permanent or intermittent streams; (b) 0.1-ha plot locations; (c) randomly sampled polygons; (d) estimated canopy cover in 1900; (e) canopy cover in 1997; (f) key for canopy cover. Canopy cover data are from Fornwalt *et al.* (2002). Linear polygons from the lower left to upper right corner of (d) and (e) reflect a twentieth century power line right-of-way. The asterisk in (e) marks an opening created by a fire in 1851.

35-km^2 landscape, four scarred a majority of the 61 trees sampled in the 4-km^2 study area and are believed to have burned the entire 4-km^2 area (Brown *et al.*, 1999). These fires were in 1587, 1631, 1723 and 1851. Other fires scarred four to 16 trees mainly in southern portions of the 4-km^2 area; these fire years were in 1534, 1686, 1700, 1775, 1841 and 1963.

One of our goals was to use tree age data to predict where past fires were stand replacing in the Cheesman Lake landscape and, if possible, spatial and temporal patterns of initial tree recruitment and subsequent stand establishment after fire. Kipfmueller and Baker (1998) compared three different methods for detecting the date of the last stand-replacing fire in forests of lodgepole pine ~150 km north of the Cheesman study area. In both young (120-year-old) and old (326-year-old) stands, the trees established soon after the last fire were reliably detected from a sample of five to 10 of the largest trees in the stand. In our studies, we identified the five oldest trees in each polygon of the Cheesman landscape on the basis of both tree size and crown morphology (Kaufmann, 1996). We sampled the ages of the five oldest trees (selected by appearance) in more than 200 randomly selected forest polygons (regardless of polygon size) distributed across the 35-km^2 landscape (Huckaby *et al.*, 2001). All tree cores collected for this study and fire scars sampled by Brown *et al.* (1999) were prepared and cross-dated using standard dendrochronological techniques (Stokes and Smiley, 1968). Kaufmann *et al.* (2000b) describe the methods used to estimate the germination year from tree cores collected 30–40 cm above the ground. The polygons sampled in the 4-km^2 area are shown in Figure 1c.

We hypothesized that where all tree ages sampled in a polygon post-dated an individual fire, the fire might be presumed to have been stand-replacing in that polygon (Kaufmann *et al.*, 2000a). Furthermore, we hypothesized that the age of the oldest post-fire tree indicates the time required for reforestation to begin after the stand-replacing event. If successful, the proportion of polygons having trees pre-dating or post-dating a given fire could be used to estimate the percentage of the entire study area that might have experienced stand-replacing fire intensity for that fire, recognizing that subsequent fires and other natural disturbances affected tree survival and may affect the interpretation of fire and tree recruitment histories (discussed later). The potential effect of polygon or plot aspect on reforestation time after fire was evaluated using the Bonferroni-adjusted Wilcoxon rank sum test.

We used intensively sampled trees ages from 0.1-ha plots to test this use of the ages of the five oldest trees in the larger-scale polygon sample. The ages of 20 randomly selected trees were determined in each of 25, 0.1-ha plots randomly distributed throughout the 4-km^2 area, stratified by aspect (Figure 1b). A total of three old trees not randomly selected in the 25 plots were added to increase the likelihood that the oldest trees had been identified. The 0.1-ha plot data were compared with the data for the five oldest trees sampled in the polygons. Concurrence tests were done on data categorized according to intervals between the large fires (FREQ procedure; SAS, 1999). These frequency data were used to compare (1) the age distributions based on the oldest tree in each 0.1-ha plot and polygon, (2) the five oldest trees in each plot and polygon and (3) all trees sampled. We hypothesized that the oldest tree comparison would indicate no difference between the plots and polygons. However, the five oldest trees in plots may differ from the five oldest trees in polygons because in the plot study trees were sampled randomly, whereas in the polygon study sampling focused exclusively on the old trees; also, the plots were generally much smaller than the polygons (Figure 1b and c). Similarly, we expected no agreement between the total age sample for the 0.1-ha plots and the five oldest trees in the polygons. Chi-squared analyses were used to compare the plot and polygon frequencies between fires. In addition, a Kolmogorov-Smirnov test was run on the cumulative frequency distribution of the oldest tree in all plots and polygons to test the hypothesis that the two distributions were similar (NPAR1WAY procedure; SAS, 1999).

Results

Predicting fire effects on forest structure from tree ages

Tree age data from 25 plots (0.1-ha) were used to test if the ages of the five oldest trees could be used to identify a major preceding fire that might have been stand replacing at that site. Age data for 20 trees per plot are shown in Figure 2 (top), where each 0.1-ha plot is represented with a time line marked with the estimated germination year of each tree. Several observations are possible from the 0.1-ha plot data. First, the age distribution of the five oldest trees varied widely in some plots, but in other plots the ages of the five oldest trees were similar. Trees older than 400 years were observed, and often the age range for the five oldest surviving trees exceeded 200 years. Plots where the age range of the five oldest trees was less than 50 years post-dated 1800. Secondly, we anticipated from the fire history and tree age data for the entire 35-km^2 landscape that the 1587, 1631, 1723 and 1851 fires had major influences on forest structure. However, it appears that more 0.1-ha plots post-dated the 1534 fire and predated 1587 than post-dated either the 1587 or 1631 fire (Table 1). Later we discuss precautions about attributing the age structure of older stands to fire effects. The majority of the plots appeared to post-date 1723, and one predated the 1534 fire. Finally, only three 0.1-ha plots included in Table 1 had their oldest surviving tree post-dating any of the smaller fires, one following 1700 and two between 1841 and 1851. Locations of those plots and the fires associated with them coincided. For later analyses, we lumped these plots with those related to the previous larger fire.

The ages of the oldest trees in polygons sampled in the 4-km^2 study area (Figure 1c) are shown in Figure 2 (bottom). Conclusions reached for the polygons sampled in the 4-km^2 area are identical to those reached for the 0.1-ha plots (above). The percentage of all polygons with their oldest trees post-dating individual past fires

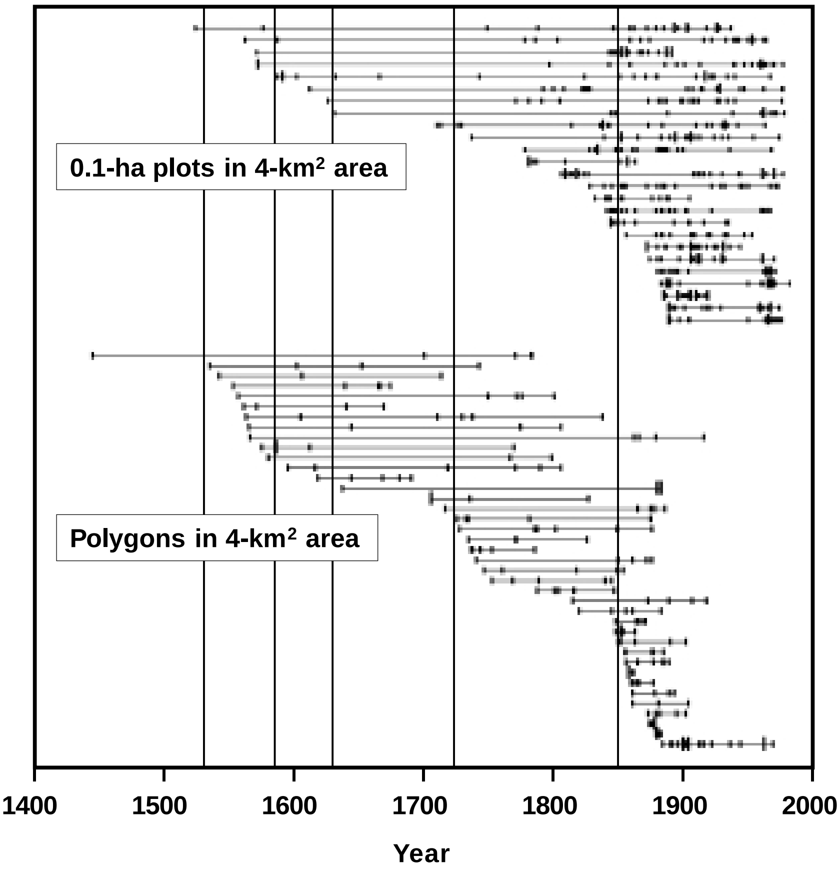

Figure 2. Age distribution of trees sampled in the 4-km^2 study area at Cheesman Lake, Colorado, USA: (top) 25 plots (0.1-ha); (bottom) randomly sampled polygons. Each horizontal line is a time line for individual 0.1-ha plots or polygons in the 4-km^2 area, spanning the age range for the sampled trees. Each vertical bar represents the estimated germination year of sampled trees, with a longer bar for two trees. Major fire years are shown as vertical lines through both data sets. Data are displayed using FHX-2, a fire history program (Grissino-Mayer, 2001).

(including the smaller fires) are shown in Table 1. Chi-squared analyses comparing the plot and polygon frequencies between fires required combining earlier fire periods to have sufficient category frequency. Chi-squared categories used were <1723, 1723–1851 and >1851. These analyses indicated that the frequencies of the oldest trees in each category were not significantly different between the plots and polygons (P = 0.855). As expected, comparisons using the five oldest trees versus all trees sampled per plot or polygon were significantly different (P = 0.003), because the trees represented different proportions of their respective populations. However, the Kolmogorov-Smirnov test of the cumulative frequency distribution of the oldest-tree ages for the 0.1-ha plots and polygons confirmed that the frequency distributions were similar.

As a final evaluation, we examined several tree age samples that were linked spatially. In one case, three 0.1-ha plots were sampled within one polygon. In all three plots, the oldest tree postdated 1534 and pre-dated 1587. In another case, a polygon and a 0.1-ha plot within it both identified 1723 as the preceding fire. These comparisons indicate general consistency among sampling techniques; however, sampling in large polygons may fail to detect that a more recent fire

Table 1: Number and percentage of total 0.1-ha plots or polygons in which the oldest surviving tree post-dated one fire and pre-dated the next, Cheesman Lake landscape, Colorado, USA (stands that post-date the 1534 fire but pre-date the 1587 fire are interpreted as having become established after the 1534 fire, and similarly for the other stand establishment dates)

	Plots pre-dating next fire		Polygons pre-dating next fire	
Pre-dating fire	No.	%	No.	%
Pre-1534	1	4	1	3
1534	4	16	10	26
1587	2	8	2	5
1631	1	4	3	8
1700	1	4	–	–
1723	6	24	12	31
1841	2	8	–	–
1851	8	32	11	28
Total	25	100	39	100

influenced only a portion of the polygon. This suggests that sampling of the five oldest trees is a useful technique, but limitations in the interpretation of data are to be noted.

Persistence of openings after stand-replacing fire

We have long suspected that tree recruitment after fire was delayed for variable periods, particularly on harsher sites. Even with a century of fire suppression, openings or areas with very few trees still existed on south slopes in the landscape near the north end of the 4-km^2 area (Kaufmann *et al.*, 2000a, b, 2001). In each such opening examined, charred tree remnants having intact bark indicated the death year was 1851, the date of the last known fire in most of the 4-km^2 area (Brown *et al.*, 1999). Each of the data sets reported here suggests that the oldest tree post-dates a preceding fire by times varying from a few years to more than a century. In one 26-ha polygon on a south aspect, the fire in 1851 apparently killed all trees, and the current canopy cover is <10 per cent (see large white polygon marked with an asterisk near the left end of the upper 4-km^2 boundary in Figure 1e). A transect was used to sample the ages of the scattered trees now established (see Figure 2 bottom, the very last polygon). Ages of these trees indicated gradual establishment between 1885 and 1970, with some areas currently having only several trees per hectare and other areas having none.

We used the oldest tree in each polygon and plot classified according to the fires pre-dating the oldest tree to determine the time delay to tree establishment (Table 2). Plots and polygons also were analysed, according to aspect, to test if trees regenerated on north aspects more quickly than on other aspects. We recognize potential limitations caused by tree attrition from causes other than fire and discuss these limitations below. These data indicate wide ranges in time between the pre-dating fire and recruitment of the oldest surviving post-fire tree, in both plots and polygons and north versus other aspects. When both aspect categories were combined, a *t*-test indicated that 0.1-ha plots had a significantly (P = 0.030) higher mean number of years between fire and the oldest surviving tree. When analysed within aspect, only the Other Aspects category was significantly different (Bonferroni-adjusted Wilcoxon rank sum test P = 0.024), with mean plot years (45.9) longer than the polygon mean (23.4). This appeared to be related to three 0.1-ha plots with large recruitment delays after the 1723 fire.

Discussion

Restoration of forests that historically were regulated by fire and other natural disturbance processes is being addressed globally. In many locations, current forests are dramatically different from historical forests, and major changes in forest structure are required to restore

Table 2: Time between previous fire and age of the oldest tree in polygons or 0.1-ha plots on north aspects and all other aspects, Cheesman Lake landscape, Colorado, USA

	North aspect								Other aspects							
	0.1-ha plots				Polygons				0.1-ha plots				Polygons			
Pre-dating fire	*N*	Mean	SD	Range	*N*	Mean	SD	Range	*N*	Mean	SD	Range	*N*	Mean	SD	Range
<1534	1	–	–	–	1	–		–					1	–	–	–
1534	1	26	–	–	2	36	9.9	29–43	4	35	0.5	35–36	7	26	15.4	3–48
1587	1	0	–	–	1	33	–	–	2	30	9.9	23–37	1	10	–	–
1631					1	8	–	–	1	0	–	–	1	4	–	–
1696	1	12	–	–	1	22	–	–					1	11	–	–
1723					5	24	28.0	4–73	6	81	41.3	12–119	18	32	31.9	0–98
1851	4	27	7.9	19–36	1	11	–	–	4	23	14.8	3–36	12	13	12.0	0–34
Overall	7	20.6	11.9	0–36	11	24.2	20.1	4–73	17	45.9	37.0	0–119	40	23.4	24.7	0–98

N is the number of plots or polygons; means and ranges are in years.

Only polygons having more than 10 per cent canopy cover or 0.1-ha plots having 20 trees or more in 1997 were sampled. Overall statistics did not include the pre-1534 plots and polygons.

forests similar to those that occurred historically (e.g. Nordlind and Östlund, 2003). Even where reserves of historical forests have been protected, overall landscape structure and processes have been lost through fragmentation, or drastically changed through intensive management and exploitation (Carey, 2003). Nearly all ponderosa pine forests have been altered significantly by human activities, and current forest structures often bear little resemblance to historical forests (Fulé *et al.*, 1997).

We are confident that the historical landscape at Cheesman Lake was much less dense than the current landscape. Reconstructed canopy cover in 1900 was dramatically lower than canopy cover estimated from 1996 aerial photographs, suggesting increases in stand density during the twentieth century that we have attributed to fire suppression (Figure 1d and e; Fornwalt *et al.*, 2002). Historical photographs confirm that forests were patchy and low in density (Kaufmann *et al.*, 2001). Reconstructing the temporal and spatial patterns of past fires and tree recruitment provides valuable insight into the major factors regulating historical landscapes and their changes over time (Donnegan *et al.*, 2001; Veblen *et al.*, 2000). This knowledge is important for determining appropriate recommendations for restoring landscapes. In the absence of historical insight, it is difficult to know how to restore landscapes to a sustainable condition in which natural regulatory processes could once again occur.

Fire history by itself is inadequate to interpret historical forest structure at a landscape scale. Spatially explicit tree age data also are needed for reconstructing historical patch conditions that collectively form a landscape. In any study of historical landscape structure, tree attrition affects the ability to reconstruct past forest structure and temporal changes in relation to past fires and other natural disturbances. Logging and other human effects such as burning undoubtedly affect our ability to quantify temporal and spatial patterns in tree establishment for earlier natural disturbance events, because needed evidence is lost. The lack of logging and suppression of fires at Cheesman Lake protected this evidence.

At the 4-km^2 study area at Cheesman Lake, only one significant fire (1851) is likely to have killed many trees since 1723, and on many sites a large population of trees predated 1851. A small fire in 1963 was not stand replacing. It appears that even with probable attrition of some trees established after the earlier fires prior to 1723, the times between the previous fire and oldest recently surviving tree had about the same means, ranges and distribution as for the more recent fires. This suggests that delays of tree recruitment can be estimated with reasonable accuracy, even for the earlier fires, by identifying the oldest tree through sampling of the five oldest trees in a polygon. Natural mortality of ponderosa pine from causes other than fire (e.g. insects, lightning) probably contributed substantially to loss of trees regenerating over 400 or 450 years ago, suggesting that the 1534 fire may have had less influence as a stand-replacing event than implied by the tree age data. Nonetheless, we observed trees older than 500 and 600 years in various places in the 35-km^2 landscape, suggesting that trees survived multiple natural disturbances, even pre-dating 1534. Fire scar sample analysis for the whole landscape indicated discernable recruitment pulses after fires in 1496 and 1534 (Brown *et al.*, 1999; Figure 2). Kaufmann *et al.* (2000b) discussed various natural disturbances and concluded that only fire was likely to cause complete stand replacement in these forests.

Data presented here focus on ponderosa pine, a species that is adapted to survive fire, growing in a region where conditions historically favoured less frequent mixed severity fires (~50 years apart) than the more frequent low intensity surface fires (<10 year interval) in the south-western US. The Cheesman Lake data illustrate how, at a local scale, variations in fire severity (stand-replacing versus non-stand-replacing portions of mixed severity fires) and delays in tree recruitment after stand-replacing fire combined to regulate the landscape mosaic and its changes over time. Together, historical mixed severity fires and delays of regeneration into openings created by fire contributed to a very open, spatially complex and temporally dynamic landscape structure. In contrast, where low intensity surface fires dominated historical ponderosa pine forests, landscapes may have been more uniform spatially. In other forest systems containing lodgepole pine or other species that regenerate readily after fire, or where resprouting is common (such as aspen (*Populus tremuloides* Michx.)), large crown fires resulted in even-aged stands with low spatial heterogeneity.

Restoration goals aimed toward ecological sustainability depend upon historical fire behaviour and tree recruitment patterns. Findings reported here and elsewhere (Kaufmann and Hessel, 2000; Kaufmann *et al.*, 2001) on ponderosa pine having a historical mixed severity fire regime suggest several specific restoration goals for forests in the South Platte watershed and Colorado Front Range. First, openings of various sizes should be created, amounting to 15–25 per cent of the landscape. Secondly, major reductions in tree density are needed, especially in smaller diameter classes, resulting in canopy covers of 10–30 per cent over most of the landscape. Thirdly, most Douglas-fir trees should be removed, except on north aspects where they should be thinned. Fourthly, old trees (200 years or older) should be retained. In the historical Cheesman Lake landscape, trees 300–500 years old were common. And fifthly, fire should be re-introduced to minimize ingrowth of new trees.

Restoration of Colorado Front Range ponderosa pine forests provide several key benefits. One is that sustainable ecological conditions could be restored, with forest restructuring reducing the likelihood of catastrophic fires. Five such fires have occurred since 1996, burning a total of 70 000–75 000 ha, much at high severity over larger areas (patch sizes) than occurred historically. Restoration of historical forest densities and landscape heterogeneity would benefit the Pawnee montane skipper (*Hesperia leonardus montana*), a threatened species requiring openings in the forest and, undoubtedly, would benefit many species that favour more open forest conditions. Furthermore, restoration would help reduce wildfire hazards where people inhabit forest lands. Thus in these forests, thinning and re-introducing landscape heterogeneity are suitable treatments meeting several objectives. The greatest limitations for accomplishing treatments involve the high economic costs associated with thinning forests that have an over-abundance of small-diameter trees, and concerns about potential unintended consequences of restoration activities, such as the introduction or spread of noxious weeds, construction of roads, etc. Nonetheless, the scientific basis for landscape restoration activities is considered to be strong, and unintended outcomes are detectable at early stages during the monitoring phase of adaptive management.

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