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ORIGINAL ARTICLE

# Spatial and temporal variation in historic fire regimes in subalpine forests across the Colorado Front Range in Rocky Mountain National Park, Colorado, USA

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## ABSTRACT

**Aim** The historical variability of fire regimes must be understood in the context of drivers of the occurrence of fire operating at a range of spatial scales from local site conditions to broad-scale climatic variation. In the present study we examine fire history and variations in the fire regime at multiple spatial and temporal scales for subalpine forests of Engelmann spruce–subalpine fir (*Picea engelmannii*, *Abies lasiocarpa*) and lodgepole pine (*Pinus contorta*) of the southern Rocky Mountains.

**Location** The study area is the subalpine zone of spruce–fir and lodgepole pine forests in the southern sector of Rocky Mountain National Park (ROMO), Colorado, USA, which straddles the continental divide of the northern Colorado Front Range (40°20′ N and 105°40′ W).

**Methods** We used a combination of dendroecological and Geographic Information System methods to reconstruct fire history, including fire year, severity and extent at the forest patch level, for *c*. 30,000 ha of subalpine forest. We aggregated fire history information at appropriate spatial scales to test for drivers of the fire regime at local, meso, and regional scales.

**Results** The fire histories covered *c*. 30,000 ha of forest and were based on a total of 676 partial cross-sections of fire-scarred trees and 6152 tree-core age samples. The subalpine forest fire regime of ROMO is dominated by infrequent, extensive, stand-replacing fire events, whereas surface fires affected only 1–3% of the forested area.

**Main conclusions** Local-scale influences on fire regimes are reflected by differences in the relative proportions of stands of different ages between the lodgepole pine and spruce–fir forest types. Lodgepole pine stands all originated following fires in the last 400 years; in contrast, large areas of spruce–fir forests consisted of stands not affected by fire in the past 400 years. Meso-scale influences on fire regimes are reflected by fewer but larger fires on the west vs. east side of the continental divide. These differences appear to be explained by less frequent and severe drought on the west side, and by the spread of fires from lower-elevation mixed-conifer montane forests on the east side. Regional-scale climatic variation is the primary driver of infrequent, large fire events, but its effects are modulated by local- and meso-scale abiotic and biotic factors. The low incidence of fire during the period of fire-suppression policy in the twentieth century is not unique in comparison with the previous 300 years of fire history. There is no evidence that fire suppression has resulted in either the fire regime or current forest conditions being outside their historic ranges of variability during the past 400 years. Furthermore, in the context of fuel treatments to reduce fire hazard, regardless of restoration goals, the association of extremely large and severe fires with infrequent and exceptional drought calls into question the future effectiveness of tree thinning to mitigate fire hazard in the subalpine zone.



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**Keywords**

*Abies lasiocarpa*, climatic influences, fire history, forest dynamics, North America, *Picea engelmannii*, *Pinus contorta*, Rocky Mountains, subalpine forests.

## INTRODUCTION

Wildfire patterns in western North American forests are controlled by multiple factors ranging from stand-scale fuel conditions to regional climatic variation, which act synergistically to determine the characteristics of the fire regime such as frequency, size and severity of fires. However, we have a relatively poor understanding of these interactions and their consequences for current forest conditions and resource management issues (Lertzman & Fall, 1998). The factors driving ecosystem processes are sometimes classified as bottom-up (i.e. local) or top-down (i.e. regional) in nature (Levin, 1992; Lertzman & Fall, 1998). In the case of fire regimes, this dichotomy stresses potential differences between the relative importance of local influences such as site productivity and fuel patterns vs. regional influences of fire weather (Heyerdahl *et al.*, 2001). At one end of this continuum are fire regimes viewed as driven primarily by accumulation of fuel (e.g. Minnich *et al.*, 1993), and at the opposite end are regimes in which fire weather is considered the primary or sole driving factor (Bessie & Johnson, 1995). Clearly, the applicability of these opposite views varies geographically and by type of ecosystem. A recent review of fire regimes in Rocky Mountain subalpine forests concluded that the effects of climatic variability on fire regimes are contingent on the spatial features of the local landscape, but also noted a lack of specific studies on how these drivers interact (Baker, 2003). In the context of management of the forest ecosystem in Rocky Mountain forests, we need improved understanding of the drivers of fire regimes and their interactions which determine the spatial heterogeneity of fire regimes. The goal of the present study is to assess the relative importance of potential driving factors originating across a range of spatial scales for the fire regime of the subalpine forest zone of the southern sector of Rocky Mountain National Park (ROMO) in the northern Colorado Front Range.

Infrequent stand-replacing fires are believed to have shaped the structure of the subalpine forests of lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) in the US Rocky Mountains (Arno, 1980; Romme & Knight, 1981; Romme, 1982; Kipfmueller & Baker, 2000; Peet, 2000; Veblen, 2000). Surface fires also occur in these subalpine forests, and most studies have concluded that they affect only a small percentage of the surface area of the forests studied (Huckaby & Moir, 1995; Kipfmueller & Baker, 2000; Sibold, 2001; Buechling & Baker, 2004) and/or are limited to specific types of site such as habitats near the tree line (Sherriff *et al.*, 2001). However, resource managers have also suggested that surface fires formerly played a major role in some lodgepole pine forests in the Rocky Mountains, and in at least one prominent study this conclusion is central to managers' plans to restore the historic range of fire and forest conditions (McNicoll & Hann, 2004). At a regional scale, synoptic climate variability is considered to be the dominant driver of the occurrence of fire in subalpine forests in the US Rocky Mountains (Despain, 1991; Turner & Romme, 1994; Veblen, 2000; Baker, 2003; Buechling & Baker, 2004). The occurrence of fire appears to be dependent on extreme drought (Romme & Despain, 1989; Renkin & Despain, 1992; Baker, 2003; Buechling & Baker, 2004) that creates synchrony in the occurrence of fire over large areas of the subalpine zone (e.g. Wyoming and Colorado; Kipfmueller & Baker, 2000).

Despite the consensus that fire regimes in the subalpine zone of the Rocky Mountain region are driven primarily by fire weather, other non-climatic factors appear to also significantly influence fire regimes. For example, at the local scale forest structure can influence type and spread of fire (Loope & Gruell, 1973). A combination of forest type and topographical position appears to account for the less frequent occurrence of fire in spruce–fir forests in mesic ravines in comparison with adjacent xeric sites of lodgepole pine (Romme & Knight, 1981). Yet in other places such local topographical influences on fire regimes may either be relatively unimportant (Baker & Kipfmueller, 2001) or overridden by regional-scale fire weather (Despain, 1991; Turner & Romme, 1994). Nevertheless, even in extreme fire events such as the 1988 fires in Yellowstone National Park, the heterogeneity of the vegetation affected burn intensity which in turn influenced post-fire recovery and potentially affects subsequent fire hazard (Turner *et al.*, 1994).

In addition to local- and regional-scale influences, fire regimes in mountainous areas are likely to reflect meso-scale topographical and landscape influences at an intermediate scale over distances of *c.* 15–30 km. Because mountainous terrain can create spatial variations in both climatic conditions and ecological neighbourhood effects, the location and orientation of a valley relative to the broader mountain setting may influence the fire regime. Climatically, the physical characteristics and orientation of mountain ranges with respect to prevailing weather patterns can alter wind patterns, snow accumulation and amount of precipitation (Barry, 1992). These topo-climatic spatial variations have the potential to create corresponding spatial variations in the fire regime through the alteration of both the length of the fire season and the intensity and frequency of droughts. Likewise, topo-climatic gradients influence the mesoscale pattern of vegetation which can potentially juxtapose vegetation types of different fire regimes that may in turn alter fire frequency and spread into neighbouring vegetation types. Also likely to be important at mesoscales are the effects of past and present land use on fire regimes, which may explain some of the sharp contrasts reported from fire history studies in different regions. For example, in some subalpine forests fire suppression activities are believed to have effectively reduced the frequency of fires since the early twentieth century (Wadleigh & Jenkins, 1996; Kipfmueller & Baker, 2000). In contrast, in other subalpine Rocky Mountain forests, fire history studies have not shown a significant influence of fire suppression (Romme & Despain, 1989).

Subalpine fire history studies in the southern Rockies are relatively limited in number and in attempts to systematically examine spatial variations in fire regimes that may elucidate the relative importance of potential driving factors of fire regimes. Consequently, we conducted the present study of fire history in a *c.* 30,000 ha area of subalpine forest in ROMO to examine fire history as it varies spatially among drainages and across the continental divide of the Front Range. Our working hypothesis is that factors originating at a range of scales from regional through meso to local scales should have a detectable influence on the fire regimes in these forests. To test this, we aggregated information on fire history at scales appropriate to detect influences at the three scales of interest. Specifically, we aggregated and compared fire history for:

1. The forest cover types of lodgepole pine vs. spruce–fir because these two forest types integrate local differences in biophysical factors potentially influencing fire regimes.
2. Individual drainages on the east vs. west sides of the continental divide to test for effects related to meso-scale climate and neighbouring vegetation [i.e. the presence of montane forests of ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) on the east side vs. their near absence on the west side].
3. All fire years on the east vs. west side of the continental divide to test for cross-divide similarities in relationships between the occurrence of fire and regional-scale climatic variability.

## STUDY AREA

The study area encompasses *c.* 30,000 ha of subalpine forests in ROMO ranging in elevation from 2650 to 3450 m and straddling the continental divide in the Northern Colorado Front Range, Colorado, USA (40°20′ N and 105°40′ W; Fig. 1). The study area is divided into five drainages, three on the west and two on the east sides of the divide, each of roughly equal size (*c.* 5000–7000 ha), forest composition and topographic complexity.

The region has a continental climate, with a gradient of increasing winter–spring precipitation towards the northwest due to orographic uplift of westerly maritime air masses (Kittel *et al.*, 2002). The Grand Lake (2590 m) and Allens Park (2575 m) climate stations, located on the western and eastern edges of the study area, respectively, record similar climatic patterns (Colorado Climate Center, 2002). Both stations report an average of just over 500 mm of precipitation per year with peaks in spring and summer. Average temperatures are about 0 °C in the winter and 22.5 °C in the summer. Summer thunderstorms with lightning are common on both sides of the divide. The most significant difference between the two stations is the approximately 1-month longer-lasting snowpack into early June at Grand Lake (Colorado Climate Center, 2002). Generally, the amount of snowfall west of the divide is higher and less variable annually in comparison with the east side of the divide (Changnon *et al.*, 1991).

In the study area of subalpine forests, lodgepole pine forests dominate lower elevations and xeric south-facing slopes whereas Engelmann spruce–subalpine fir forests typify the higher elevations and more mesic, north-facing slopes. Many of the post-fire lodgepole pine stands on mesic sites are successional to spruce–fir (Peet, 1981). Small areas dominated by limber pine (*Pinus flexilis*), Douglas fir (*P. menziesii*), and/or aspen (*Populus tremuloides*) accounted for less than 2% of the forested area of the study area and are excluded from our analyses. On the west side of ROMO, the lower elevation limit of the study area is mainly bordered by Grand Lake and park vegetation (meadow and shrubs), whereas on the east side the subalpine forest is bordered by montane ponderosa pine and Douglas fir (i.e. mixed conifer) forests. These montane forest types constitute the lower border of 4% and 91% of the subalpine cover types on the west and east sides of the study area, respectively.

Following Euro-American settlement in the mid-1800s, very limited parts of the study area were affected by mining, logging and ranching until the establishment of the Park in 1915 (Buchholtz, 1983). Fire suppression began in ROMO in 1920 but was not considered effective until about 1929 (Hess, 1993). Since the establishment of the Park in 1915, only seven fires of > 3 ha have occurred in the study area (Table 1). The fire suppression policy was briefly changed to a let-burn policy in 1972 that permitted natural fires, but the policy was abandoned as a result of the 1978 Ouzel burn that threatened nearby homes (Hess, 1993). Prescribed fire in ROMO has been employed primarily in the ponderosa pine forest type of the montane zone and has not had a significant impact within the subalpine zone.

## METHODS

We used dendroecological and Geographic Information System (GIS) techniques to examine fire history at the forest-patch scale (8–930 ha) for five watersheds of subalpine forests (Table 2). The five drainages, treated as sub-study areas, were similar in size, forest cover type and topographical complexity. Mean values of elevation, slope and aspect derived for the forested portion of each sub-area from a 30-m resolution digital elevation model were not significantly different among sub-areas (Kruskal–Wallis test; $P < 0.05$).

To identify forest patches of potentially homogeneous fire history for field sampling we used the vegetation layer of the Rocky Mountain National Park GIS (1995). Because forest characteristics can be related to the time since the last fire, forest patches of varying characteristics can be used as a starting point to spatially investigate fire history (e.g. Veblen

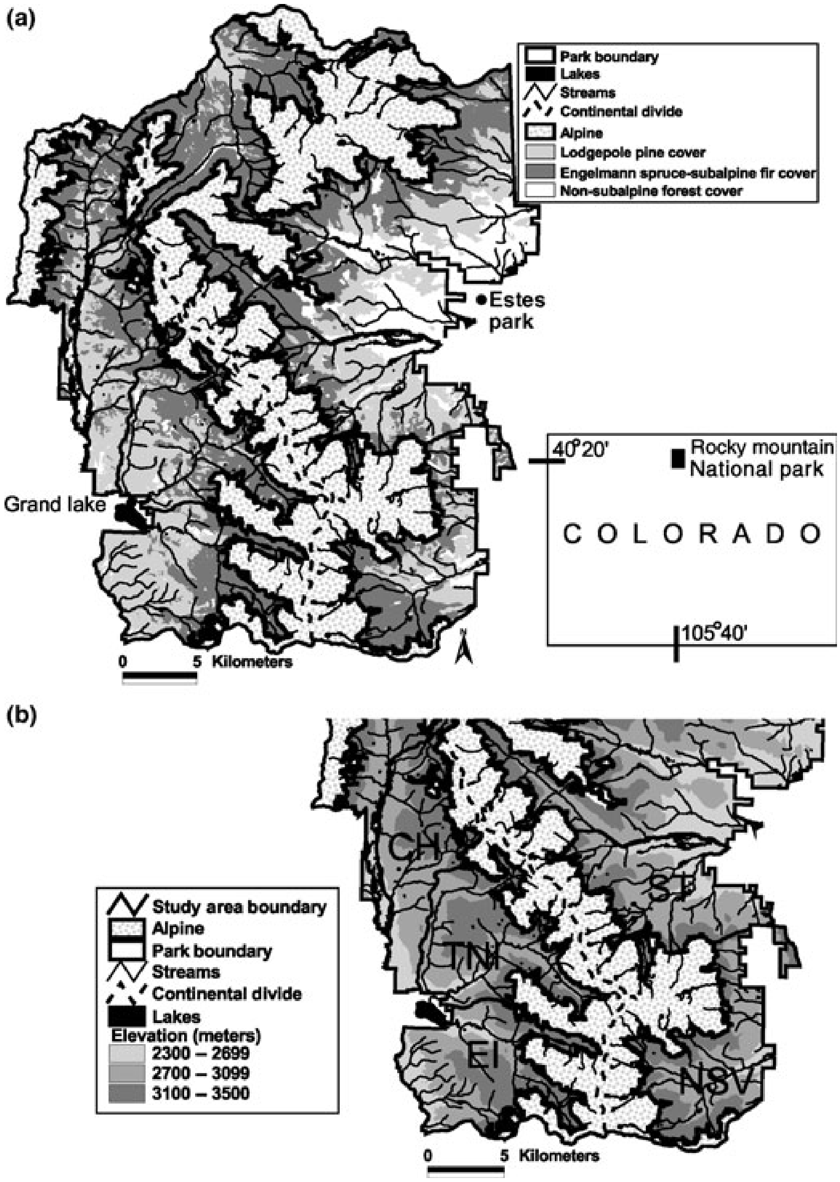


**Figure 1** (a) Map showing the location of the study area and the distribution of lodgepole pine and Engelmann spruce–subalpine fir forest cover types within the Rocky Mountain National Park. (b) Map showing the locations and elevational gradients of the five sub-study areas in the southern section of the Rocky Mountain National Park. Sub-area abbreviations are: CH, Colorado headwaters; TNI, Tonahutu-North Inlet; EI, East Inlet; ST, South Thompson; NSV, North St Vrain.

**Table 1** Fires > 3 ha within the study area recorded in the documentary fire record of Rocky Mountain National Park, 1915 to 2002. Causes are: H, human; L, lightning; P, prescribed burn (Source: Rocky Mountain National Park, unpubl. fire history data)

| Fire name | Substudy area | Year | Cause | Area burned (ha) |
|---|---|---|---|---|
| Lake Nakoni | Tonahutu-North Inlet | 1944 | H | 10.5 |
| Mill Creek Moraine | South Thompson | 1962 | H | 3.2 |
| Cub Lake | South Thompson | 1972 | H | 16.2 |
| Ouzel | North St Vrain | 1978 | L | 425.1 |
| Paradise Park | East Inlet | 1988 | L | 8.1 |
| Moraine Park | South Thompson | 1994 | P | 50.6 |
| Cairns | East Inlet | 1994 | H | 36.4 |

*et al.*, 1994; Kipfmueller & Baker, 2000). Forest-patch boundaries in the ROMO GIS were delineated from 1:15,840 aerial photographs taken in 1987–88 and field checked in 1990–91. Based on our field observations and data analyses (see below), we aggregated many smaller patches reflecting minor site differences into larger patches of uniform fire history.

## Field methods

### *Forest-patch sampling*

In the field we located mapped patches, verified forest-patch boundaries and described and sampled their attributes. We described forest composition, tree diameter distributions and

**Table 2** Summary of dendroecological sampling of fire history evidence

| Subarea | Total area sampled (ha) | Number of cores | Number of sampling sites | Number of patches sampled | Mean number of cores per site | Number of fire-scar cross-sections |
|---|---|---|---|---|---|---|
| West of divide | | | | | | |
| Colorado headwaters | 5064 | 1044 | 80 | 67 | 13.1 | 202 |
| Tonahutu-North Inlet | 5970 | 1090 | 87 | 68 | 12.5 | 45 |
| East Inlet | 6160 | 753 | 61 | 47 | 12.3 | 77 |
| East of divide | | | | | | |
| South Thompson | 5095 | 1774 | 142 | 88 | 12.5 | 147 |
| North St Vrain | 5751 | 1491 | 117 | 66 | 12.7 | 205 |
| Total study area | 28,040 | 6152 | 487 | 336 | 12.6 | 676 |

percentage forest cover, and checked patch boundaries with the Global Positioning System (GPS) to verify these attributes in the ROMO GIS. Within patches we made an initial interpretation of fire history based on evidence of past fire including even-aged stand structures, fire-scarred trees and charred wood, which was verified by collecting tree cores at individual sites of *c.* 500 m$^2$. The number of sampling sites per patch increased with patch size (i.e. from one, two, three to four sites for successively larger patches from 8–40, 40–200, 200–500 and > 500 ha) and for patches that required extra sampling due to the complexity of their fire history. Sampling sites were located away from patch boundaries and in areas that were representative of the patch. For patches that had more than a single sampling site, we dispersed sites throughout the patch. We did not quantitatively sample patches of < 8 ha in size because they constitute a small percentage of the landscape and patches of < 8 ha are often difficult to locate; however, we located and described as many of these small patches as possible.

### *Sampling evidence of past fires*

We collected tree-core and fire-scar samples to date both stand-replacing and surface fire events following procedures similar to those that have been applied in nearby subalpine forests (Veblen *et al.*, 1994; Kipfmueller & Baker, 2000). Even-aged cohorts reflected stand origin following stand-replacing fires. To test for even-aged cohorts and determine approximate fire dates we collected about 10 cores from the trees which appeared to be the oldest of the cohort at each sample site, repeating the process when more than one cohort was present. The criteria used for selecting the oldest individual trees were: largest bole and branch diameter, absence of lower branches and small live crown-to-bole ratio. Trees were cored as close to the base as possible, angling the increment borer downward to intercept the pith of the tree at ground level. We repeatedly cored trees until we obtained a sample that either intercepted the pith or was estimated to be within about 5 years of the pith.

To determine exact fire dates for these fire-initiated patches, and to detect any surface fire events, we searched for fire-scarred trees within patches and near patch boundaries. Groups of two to four scars were collected from small areas (*c.* 400 m$^2$) to increase the likelihood of precisely dating fires (Swetnam & Baisan, 1996) and to allow for approximate mapping of the extent of surface fire. Scars were sampled by cutting a partial cross-section from trees with a handsaw (Arno & Sneck, 1977). Sample locations for tree cores and fire-scarred trees were recorded using a GPS unit and a 7.5′ USGS topographical map.

## Processing of tree-ring samples

Samples were processed according to standard dendrochronological techniques (Stokes & Smiley, 1968). Tree-core samples were counted and dated to determine the earliest ring date, initial growth rate, suppressions and releases. Marker rings, derived from regional tree-ring chronologies in the International Tree-Ring Data Bank (Deer Mountain, Hidden Valley, Onahu Creek, Milner Pass and Niwot Ridge; Graybill) and other unpublished chronologies from the region (T.T. Veblen, unpubl. data), aided in visually cross-dating samples. For cores that did not intercept the tree pith, we used Duncan's (1989) method to estimate up to 20 missing rings to the centre of the tree. For each tree-core sample initial radial growth trends based on the first 30 rings were classified as (1) rapid (i.e. steep negative exponential), (2) average (i.e. a less steep negative exponential) and (3) slow (i.e. horizontal line or positive slope). Rapid initial growth is often characteristic of a post-fire cohort (Lorimer, 1985; Veblen *et al.*, 1991). Suppressions and releases in tree growth also aided in interpreting and mapping fire events (Lorimer, 1985) and were defined as a 250% change in mean ring width sustained for 5 years compared with the previous 5 years (Veblen *et al.*, 1989). Because core samples were taken at the base of the tree by angling the increment borer downward to intercept the pith at the ground level we did not adjust estimates of tree age for coring height.

Fire-scar dates on partial cross-sections were visually cross-dated using marker rings. For difficult-to-date and dead fire-scar samples we measured tree-ring widths and quantitatively cross-dated the series. The COFECHA program (Holmes, 1983) was used to quantitatively cross-date samples against master tree-ring chronologies. Only 5% of the samples required measuring and quantitative cross-dating. If fire-scar tips occurred at a ring boundary (i.e. indicating a dormant season fire), it was assumed that the fire occurred in late summer or early autumn which is the season of most frequent occurrence of fire in the historical (1915–2002) fire record for ROMO (Rocky Mountain National Park, unpublished fire history data).

## Analytical procedures

### *Characterization of fire history and severity*

Fire history, including fire severity as stand-replacing (lethal) or surface fire (non-lethal), was determined for individual forest patches from the tree-core and fire-scar data in combination with field interpretations of forest patches. Fire-initiated patches were recognized by post-fire tree cohorts in which the oldest trees established over a relatively short period (i.e. 10–30 years) and typically displayed rapid initial growth. All stand-replacing fire dates were determined using a combination of age-class and fire-scar data. Surface fire events were interpreted from dating fire scars on surviving trees. We report the occurrence only of *spreading surface fire* events that were recorded by fire scars on at least three trees scattered throughout the patch. We do not report fire years recorded as fire scars on a single tree in or near a patch. Patches with a wide range of establishment dates (i.e. 100 years), slow initial growth of the oldest trees, non-coincident growth releases and the presence of old trees (> 400 years) were classified as 'old-forest' stands. We recognize that some of these patches may have included the remnants of old post-fire cohorts, but the recognition of post-fire cohorts older than 400 years was not feasible at all sites.

### *Development of the GIS fire history layers*

Fire history attributes for individual forest patches were added to the ROMO GIS to produce stand-origin maps (*sensu* Heinselman, 1973). For each sampled forest patch we added information about fire history including the year of last stand-replacing fire and the year of any surface fire events. Additionally, a point coverage of fire-scar locations and their dates was added to the GIS. This GIS was then used to map stand-origin dates of patches in the present-day landscape and to describe the current area of forest types and drainages that originated from fires in specific years.

To reconstruct the perimeters of past fire events, which in some cases had been burned over by more recent fires, stand-origin maps were used as the starting point. Criteria for reconstructing fire boundaries were as follows:

1. More recent fires were assumed to have burned over older burns if there was evidence (patches dating to the fire year or two or more fire scars) of the older fire in a younger patch.
2. Reconstructions were guided by the boundaries of more recent fire events, with the initial assumption that past fires were constrained by the same barriers (major streams, wet valley bottoms and rocky areas of low fuel continuity) that stopped more recent fires.
3. If there was tree-ring evidence indicating that fires did not stop at these boundaries then the fire perimeter was extended to the next potential barrier.

We also used the azimuths of fire-scars, which form on the leeward side of trees with respect to the direction of fire spread (Gutsell & Johnson, 1996), to indicate the possible direction of spread. Only the first (oldest) scar on a tree was used as a possible indicator of direction of fire spread. Because reconstructions of the extent of fire are subjective, we assigned three confidence ratings, based on the amount and quality of evidence used to reconstruct individual fire events. Fire extents were not reconstructed for the South Thompson sub-area because of the extensive recent over-burning of evidence of the old fire perimeters.

### *Descriptors of the fire regime*

We used the reconstructed fire event areas to calculate fire rotation statistics for four sub-areas. Fire rotation is the time required for the entire study area to burn once, based on the area burned per year over a given time period (Johnson & Gutsell, 1994). For the South Thompson sub-area, where recent burns prevented reliable reconstruction of past fire extents, we computed a maximum fire rotation from the map of stand origin.

We computed the mean fire interval (MFI) and the Weibull median probability interval (WMPI; Grissino-Mayer, 1995) for large stand-replacing fires for each of the five sub-areas, for each side of the divide, and the entire study area. Large events were defined as fires that either burned > 100 ha of forest area in the present-day landscape or the reconstructed landscape in a single sub-area, or fires that burned at least 50 ha of the present landscape and for which two or more fire scars and/or a patch origin date was present across a barrier (e.g. rocky areas, wet valley bottoms) to fire spread.

### *Relationships of fire regimes to drivers at local, meso- and regional scales.*

To detect influences on the fire regime at different scales, we aggregated fire history information to detect significant relationships of fire regimes to drivers at any or all of the three scales.

1. To test for possible effects of local-scale driving factors, we compared fire history for lodgepole pine vs. spruce–fir cover types within each sub-area because the former cover type reflects more xeric conditions and lower elevations than the latter (Peet, 1981; Sibold, 2001).
2. To detect possible meso-scale influences on fire regimes, data on fire frequency and size for the five sub-areas were examined for consistent trends according to location on the east vs. the west side of the divide. Given the similarities of the watersheds in terms of forest cover types and topography, the most likely explanations of any significant differences in fire history on opposite sides of the continental divide would be related to meso-scale climatic

differences or effects related to the bordering vegetation (i.e. neighbourhood effects).

3. The role of regional climate as the primary or sole driver of fire regimes was evaluated by testing for synchrony of years of widespread fire among the five sub-areas and their relationship to regional climate variability. We statistically examined fire synchrony among the five sub-areas by comparing the three individual records of large fire years from the sub-areas on the west side of the divide with the two individual records of large fires from the east side sub-areas using a 2 × 2 chi-square contingency test (Grissino-Mayer, 1995). Furthermore, we used tree-ring proxy records of climate to examine the mean climatic conditions during years of large fires (> 100 ha) and years of no or minimal burning (< 35 ha) on the *opposite* side of the divide from the climatic proxies. We used superposed epoch analysis (SEA; Grissino-Mayer, 1995) to compare mean values of the tree-ring-based reconstructions of the Palmer drought severity index (PDSI; Cook *et al.*, 1999) during fire and non-fire years. An association of years of widespread fire on the west (east) side with low PDSI (i.e. drought) on the east (west) side would imply a strong regional climatic influence.

## RESULTS

### Fire history data

We collected and processed 6152 tree-core and 676 fire-scar samples from 487 sample sites in 361 patches of homogeneous fire history in five watersheds covering a total of 27,592 ha (Table 2). Thus, over 90% of the total forested area of the study area was sampled quantitatively and an additional 4% was sampled qualitatively (Tables 2 & 3). Field checks of the patches that were too small for quantitative sampling revealed that they generally shared the fire history of neighbouring patches. Often small patches had been distinguished in the GIS vegetation layer because of slight differences in tree size, density or species composition that probably reflect slight differences in topographic position. The non-sampled area (< 6% of the forested area) consisted of patches that were too small to visit (usually much less than the 8 ha criterion).

Numbers of sampling sites relative to numbers of patches were generally higher where structural complexity was greater (i.e. greater patchiness on the east side of the divide; Table 2). The number of fire-scar samples (i.e. partial cross-sections) collected for each sub-area varied from 45 to 205 (Table 2) depending on the complexity of fire history and the availability of scarred trees. Approximately 95% of the fire-scar samples were from lodgepole pine. Fire scars were mostly (> 90%) located on the boundary of stand-replacing fires, and recorded fire dates that corresponded to cohort establishment dates from adjacent forest patches. Thus, in these subalpine forests fire scars generally recorded the dates of stand-replacing fires in contrast to widespread surface fires.

Age frequency distributions of the oldest trees in each patch, in combination with initial radial growth patterns and the presence of nearby fire-scarred trees, allowed for the identification of post-fire stands up to a maximum age of 350 years (Fig. 2). The subjectively identified oldest trees in post-fire cohorts typically established within 10–30 years of the fire-scar date, and most had initially rapid growth. In contrast to post-fire stands, old forest patches with no evidence of fire had heterogeneous stand structures, mixed tree ages (Fig. 2), slow initial radial tree growth, trees exceeding 400 years in age and no fire-scarred trees. Although some of these patches of old forest may have experienced fire at some time in the past, they have no record of fire for at least the last 400 years. These criteria were the basis for maps of stand origin of each of the five sub-areas (Fig. 3).

In addition to the stand-origin maps the approximate extents of older fires were reconstructed in four of the five sub-areas (Table 4; Fig. 4). Extreme over-burning of older fires by nineteenth century fires prevented reconstruction of the extents of older fires for the South Thompson sub-area. The reconstructed extents of the most recent fires and fires that burned within areas of older forest had high confidence ratings because they had not been over-burned (Table 4). Thus, confidence in reconstructed fire boundaries was generally lower for fires that occurred in the 1600s and for fires on the eastern side of the continental divide because of the high probability of over-burning due to the higher number of fire events east of the divide.

**Table 3** Summary of stand origins and the extent of spreading surface fires. The excluded areas consisted of patches too small for sampling

| Subarea | Total forested area (ha) | Quantitatively sampled area (ha) | Qualitatively sampled area (ha) | Excluded area (ha) | Percentage old forest (> 400 years) | Percentage post-fire forest (< 400 years) | Percentage of the landscape recording spreading surface fire |
|---|---|---|---|---|---|---|---|
| West of divide | | | | | | | |
| Colorado headwaters | 5194 | 4665 | 399 | 130 | 33 | 67 | 3 |
| Tonahutu-North Inlet | 6705 | 5582 | 388 | 735 | 26 | 74 | 1 |
| East Inlet | 7168 | 6050 | 110 | 1008 | 22 | 78 | 3 |
| East of divide | | | | | | | |
| South Thompson | 5375 | 4918 | 177 | 280 | 23 | 77 | 2 |
| North St Vrain | 5983 | 5605 | 146 | 232 | 30 | 70 | 2 |

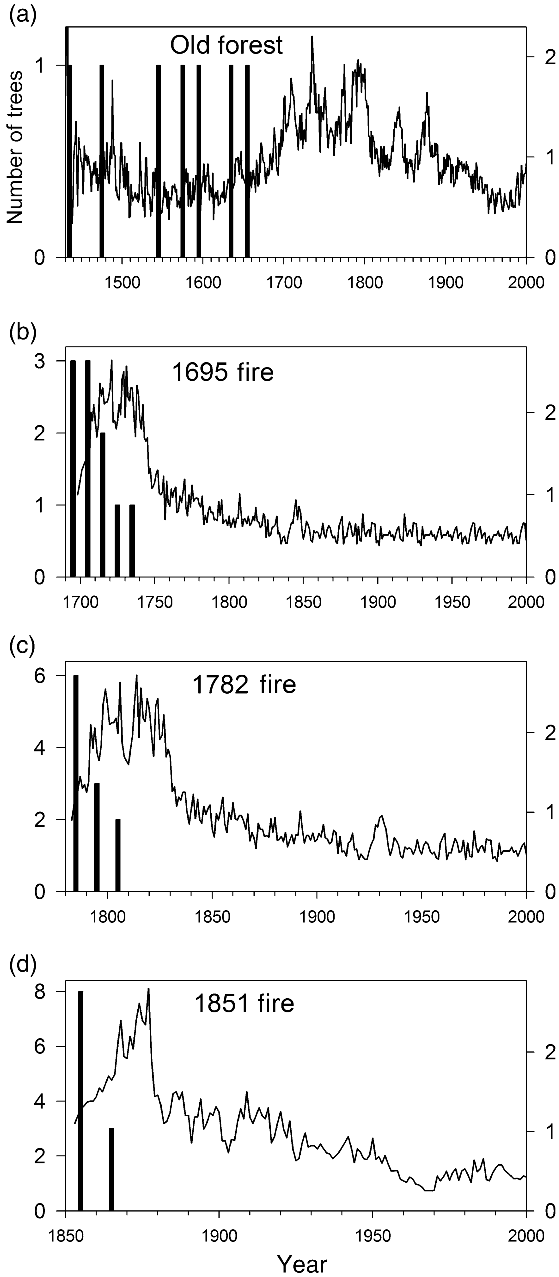


**Figure 2** Frequency distributions of establishment dates and tree-ring index values (not detrended) for the (approximately) 10 oldest trees for (a) an old forest stand and stands that established following fires in (b) 1695, (c) 1782 and (d) 1851.

## Fire history

In the entire study area, there were 22 stand-replacing fire events that each burned ≥ 5 ha of the existing forested areas from 1654 to 2002 (Table 4). The majority of forest patches recorded either stand-replacing fire or were classified as old forest indicating no fire within the past 400 years (Figs 3 & 5, Table 3). Only 1–3% of the surface areas of each subarea recorded spreading surface fire events (Table 3), and none of these patches showed evidence of multiple, frequent surface fire events.

Current forest patterns reflect widespread fires in the second half of the nineteenth century (Figs 3 & 5; Table 4). The modern landscape on the west side of the divide is dominated by patches that established following fires in 1851, 1871 and 1879 and older fires in 1695, 1708, 1730 and 1782. The modern landscape of the east side is dominated by forest patches dating from fires in 1859, 1880 and 1900 (Fig. 3). Earlier fires (e.g. 1654, 1782) were also widespread on the east side, but were largely burned over by nineteenth-century fires (Fig. 4). For the period 1695 to the present (a period when both sides of the divide have a record of fire), eight large fire events occurred on the west side of the divide while 13 occurred in an area only 59% as large on the east side of the divide (Table 4). A synchronous nearly fire-free period occurred throughout the study area from the late eighteenth century to the mid-nineteenth century; for individual sub-areas, its length ranged from 69 years (1782–1851) in Tonahutu-North Inlet and East Inlet sub-areas to 111 years (1748–1859) in South Thompson sub-area.

Reconstructed fire extents as well as extant post-fire cohorts show that fire sizes are large in relation to the area of the drainages (Table 4; Fig. 4). Fires on the west side of the continental divide burned an average of *c.* 18–25% of drainages, and 40% of fires burned more than a third of drainages (Table 4). On the east side of the divide, in the North St Vrain sub-area, the sizes of fire were relatively smaller and burned an average of *c.* 8% of the drainage; no fires on the east side burned more than a third of the drainage.

## Relationships of fire history to drivers at local, meso- and regional scales

### *Local-scale relationships*

Within the same drainage, large fire years in the lodgepole pine cover type do not always coincide with large fire years in the spruce–fir cover type (Fig. 6). The lodgepole pine cover type is more strongly dominated by stands that originated from fire events after 1850, whereas spruce–fir is dominated by older post-fire and old forest stands (Fig. 6). This general pattern is consistent throughout the study area with an average of 74% (range of 66–84%) and 13% (range of 7–21%) of the extant lodgepole pine and spruce–fir stands, respectively, establishing from post-1850 fires. Furthermore, no lodgepole pine is in the old forest category whereas 43–81% of the spruce–fir in each sub-area consisted of old stands not burned within the past 400 years (Fig. 6). The tendency for the spruce–fir cover type to burn either less frequently or less completely is reflected in large differences in rotations for the spruce–fir and lodgepole pine cover types. For the four sub-areas where fire rotation could be computed from reconstructed fire extents, the rotation periods for the lodgepole pine and spruce–fir cover types range from 162–216 years and from 401–713 years, respectively. In the South Thompson sub-area the rotation periods computed from the map of stand origin are 356 and 1146 years for the lodgepole pine and spruce–fir cover types, respectively.

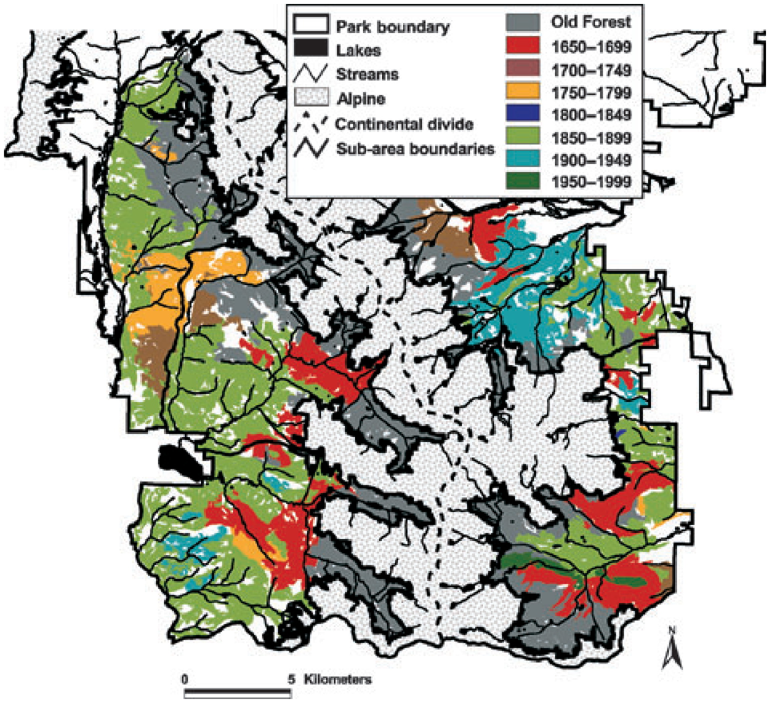


**Figure 3** Map showing dates of stand origin (i.e. the date of the last stand-replacing fire) for stands in the five sub-areas sampled for fire history in southern Rocky Mountain National Park.

**Table 4** Extent of fire based on patch size in stand-origin maps and on reconstructed fire extents for years in which > 8 ha burned. Confidence classes of reconstructed fire extents are: 1, high confidence; 2, intermediate confidence; 3, lowest confidence). Rotation times are computed from reconstructed fire extents except for the South Thompson sub-area for which it is computed from stand origins

| | Colorado headwaters | | | Tonahutu-North Inlet | | | East Inlet | | | South Thompson | North St Vrain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Area of fire (ha) | | | Area of fire (ha) | | | Area of fire (ha) | | | Area of fire (ha) | Area of fire (ha) | | |
| Fire year | SO | RE | C | SO | RE | C | SO | RE | C | SO | SO | RE | C |
| 1654 | | | | | | | | | | 230 | 685 | 1603 | 3 |
| 1675 | | | | | | | | | | 249 | | | |
| 1676 | | | | | | | | | | | 695 | 744 | 3 |
| 1695 | | | | 971 | 2972 | 2 | 1214 | 2598 | 3 | 26 | 410 | 456 | 2 |
| 1708 | 423 | 1053 | 3 | | | | | | | | | | |
| 1715 | | | | | | | | | | | 91 | 91 | 2 |
| 1730 | 5 | 705 | 3 | 836 | 921 | 2 | | | | 328 | | | |
| 1748 | 8 | 8 | 3 | | | | | | | 86 | | | |
| 1782 | 848 | 2562 | 2 | 282 | | | 177 | 177 | 1 | | 56 | 1076 | 2 |
| 1822 | | | | | | | | | | | 14 | 14 | 1 |
| 1851 | | | | 1800 | 2309 | 1 | 2668 | 4177 | 2 | | 10 | 10 | 1 |
| 1859 | | | | | | | | | | 850 | 53 | 99 | 2 |
| 1863 | | | | | | | | | | 10 | | | |
| 1871 | 1795 | 1831 | 1 | | | | | | | | | | |
| 1872 | | | | | | | | | | 205 | 101 | 101 | 1 |
| 1879 | 239 | 239 | 1 | 487 | 487 | 1 | | | | | | | |
| 1880 | | | | | | | | | | | 1486 | 1486 | 1 |
| 1893 | 36 | 36 | 1 | | | | | | | 154 | | | |
| 1900 | | | | | | | | | | 1382 | | | |
| 1902 | | | | | | | 400 | 400 | 1 | 172 | 119 | 119 | 1 |
| 1915 | | | | | | | | | | 210 | | | |
| 1978 | | | | | | | | | | | 315 | 315 | 1 |
| Fire rotation (years) | | 145 | | | 273 | | | 238 | | 405 | | 326 | |

SO, patch size from stand-origin maps; RE, reconstructed extent; C, confidence class.


**Figure 4** Maps showing the reconstructed boundaries for stand-replacing fires that had been burned over by more recent fires and for which there was enough evidence to reconstruct their boundary.

*Meso-scale relationships*

Maps of stand origin for all five sub-areas and maps of reconstructed fire extents for all sub-areas except the South Thompson sub-area indicate a pattern of larger fires on the west side (Figs 3 & 4). For example, median fire size is significantly greater on the west side (836 vs. 282 ha; $P < 0.05$; Mann–Whitney rank sum test) for large fires (> 100 ha) reflected by post-fire cohorts (Table 4). On the east side, 33% of the post-fire patches were of < 100 ha in extent vs. only 19% on the west side.

Fire intervals prior to the start of fire suppression practices in 1920 are longer on the west side than on the east side (Table 5). The Weibull median probability interval for aggregated fires is 20 years on the west vs. 13 years on the east (ranges 30–70, and 16–27 years, respectively). For individual sub-areas, mean fire intervals on the west side range from 43–69 vs. 26–31 years on the east side. Despite the longer fire intervals on the west side of the divide, the greater areas burned in individual events result in shorter fire rotations in comparison to the east side (145, 273 and 238 years on the west and 405 and 326 years on the east; Table 4). However, the rotation for the South Thompson sub-area is derived from the areas of existing post-fire stands and is longer than if the estimate were derived from reconstructed fire sizes (Van Wagner, 1978).

*Regional-scale relationships*

At the regional scale, occurrence of fire on the west and the east side of the divide is highly synchronous ($P < 0.005$; $\chi^2 = 69.66$; $2 \times 2$ contingency test) which suggests the importance of regional climatic variation as a driver of fire regimes on both sides of the divide. Fire years are characterized by a significantly below average availability of moisture (i.e. low PDSI; Fig. 7). Large fire years on one side of the divide are associated with tree-ring indicators of drought from the *opposite* side of the divide, indicating that the climatic conditions favouring fire prevailed at a regional scale (Fig. 7). Large fire years on the east side of the divide also lag above-average moisture conditions by 3 years (Fig. 7).

## DISCUSSION

### Fire history

In general, subalpine forest patches in the southern two-thirds of ROMO fall into two classes of fire history: (1) stands that originated from severe and widespread fires (73% of the forested area) or (2) stands that do not show signs of significant burning within the past 400 years (27% of the forested area). In the latter category are some stands which may have originated

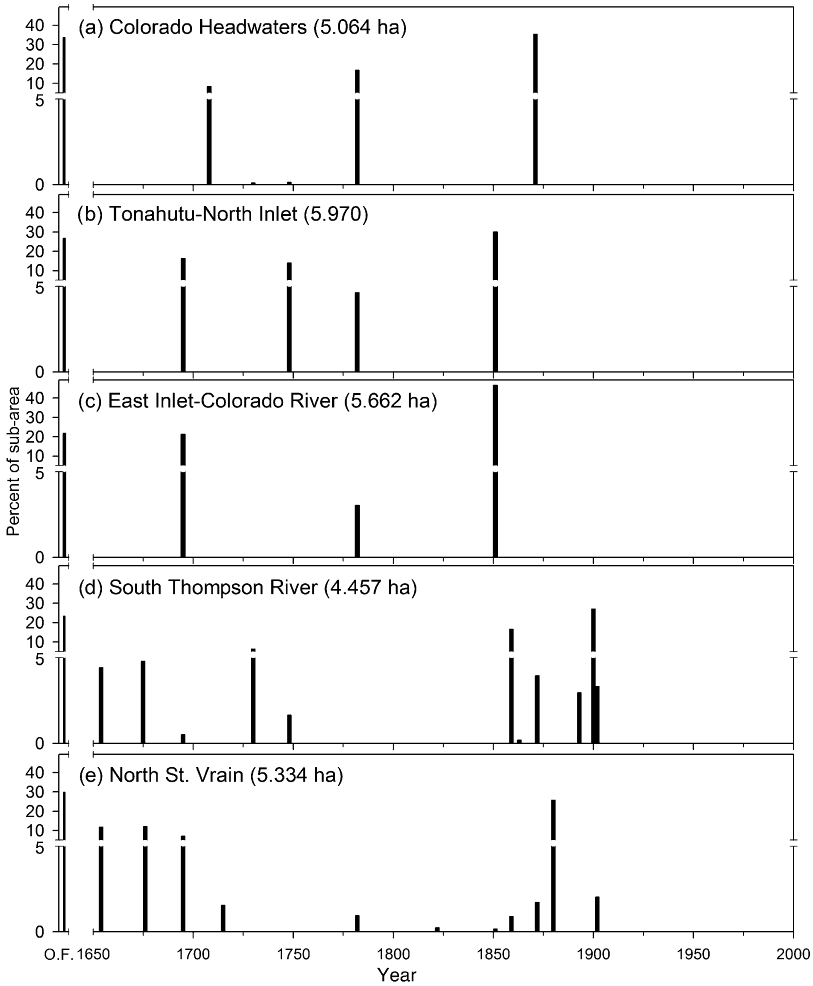


**Figure 5** The percentage of the current forested landscapes that established following individual fire years, for individual sub-areas: (a) Colorado headwaters, (b) Tonahutu-North Inlet, (c) East Inlet, (d) South Thompson and (e) North St Vrain. OF refers to forest over 400 years old.

after stand-replacing fire 400–600 years ago. However, detection of a post-fire origin for stands > 400 years old is not reliable because of the difficulty of determining total tree ages for such large, old trees and due to the low survivorship of trees of an initial post-fire cohort beyond *c.* 500 years. Thus, it is uncertain what percentage of the old forest stands are post-fire stands older than 400 years or are dominated by old trees that did not establish following a fire.

Despite the difficulties in comparing results between fire history studies because of variations in sizes, sampling intensities and characteristics between study areas (Veblen, 2003b), the general fire regime we report here is similar to those reported by other studies in lodgepole pine and spruce–fir forests in the southern Rockies (Romme & Knight, 1981; Veblen *et al.*, 1994; Kipfmueller & Baker, 2000; Buechling & Baker, 2004). The fire severity is predominantly a stand-replacing fire. Only small areas (< 3% of the entire study area) recorded any evidence of spreading surface fire, and no evidence was found of frequent surface fire events (i.e. dispersed trees recording three or more synchronous fires). Fires were large and infrequent. Individual fire events sometimes burned between 30% and 50% of the forested area of *c.* 5000–7000 ha drainage (e.g., 1695, 1851, and 1880). Although the reconstructed fire extents are necessarily estimates of older fire sizes, it is highly probable that the large fire sizes clearly recorded in the stand-origin maps for the nineteenth century were also characteristic of the fire events of the 17th and 18th centuries.

In general, fire rotations found in the current study are similar to those reported for other subalpine forests in the region. Fire rotations on the east side of the divide (Table 4) are similar to a fire rotation of 346 years for crown fires reported for a study area of 9200 ha in the northeastern portion (east side of continental divide) of ROMO (Buechling & Baker, 2004). However, Buechling & Baker (2004) report more small fire events and a larger percentage of the study area affected by surface fires (5.6%) than found in the present study. These could be real differences reflecting the inclusion of some montane cover types at low elevations in Buechling & Baker's study area, or may be due to their dating of fire scars only on increment borer samples (instead of cross-sections). Fire-scar dates on increment borer samples are less likely to be annually precise, consequently inflating the number of fire years recorded. In a subalpine forest in the nearby Medicine Bow range of Wyoming, Kipfmueller & Baker (2000) report a fire rotation of

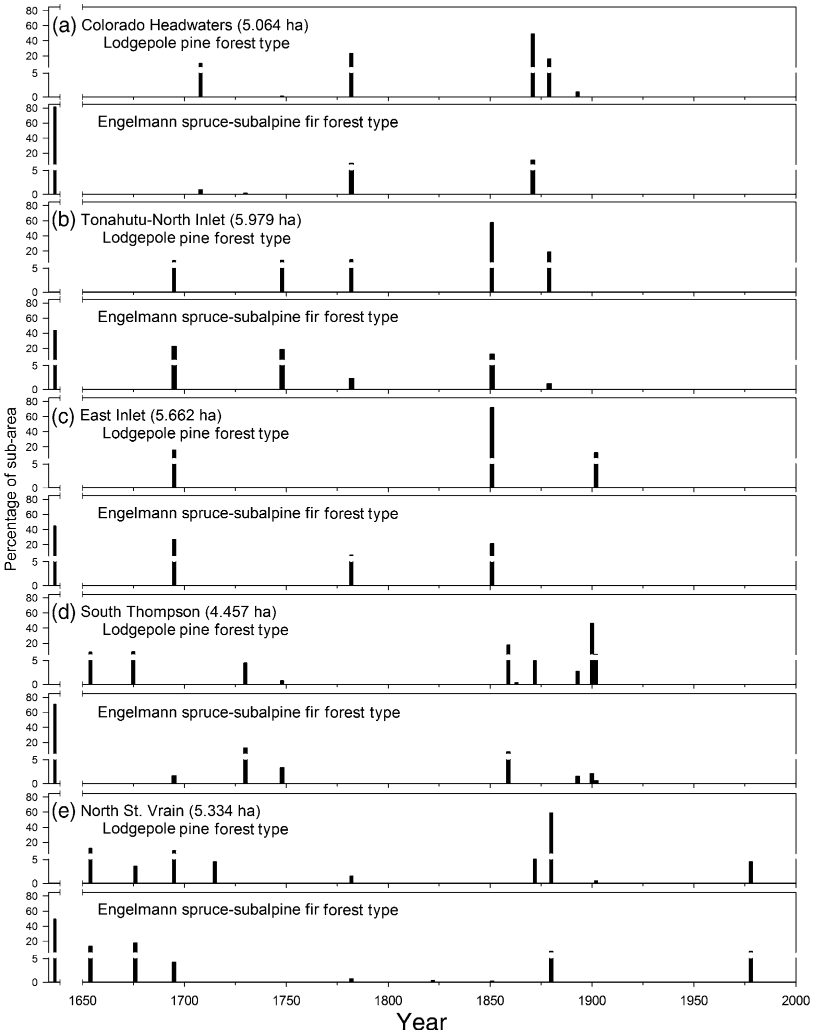


**Figure 6** The percentage of each cover type in the current landscape that established following individual fire years in sub-areas (a) Colorado headwaters, (b) Tonahutu-North Inlet, (c) East Inlet, (d) South Thompson and (e) North St. Vrain. OF refers to forest over 400 years old.

**Table 5** Fire interval statistics calculated for the period prior to fire suppression starting in 1920 for large fire years only, defined as > 100 ha of the present day landscape or > 50 ha of present day landscape and at least two scars across a barrier to fire spread (as defined in the reconstruction of fire extent)

| Subarea | Area (ha) | Years of record | NI | WMPI | MFI | Range | Min | Max | SD |
|---|---|---|---|---|---|---|---|---|---|
| West of divide | | | | | | | | | |
| Colorado headwaters | 5064 | 1708–1893 | 4 | 30 | 43 | 81 | 8 | 89 | 35 |
| Tonahutu-North Inlet | 5970 | 1695–1879 | 4 | 46 | 46 | 41 | 28 | 69 | 18 |
| East Inlet | 5662 | 1695–1902 | 3 | 70 | 69 | 36 | 51 | 87 | 18 |
| West of divide | 16,696 | 1695–1902 | 6 | 20 | 34 | 56 | 13 | 69 | 21 |
| East of divide | | | | | | | | | |
| South Thompson | 5095 | 1654–1915 | 10 | 16 | 26 | 109 | 2 | 111 | 31 |
| North St Vrain | 5751 | 1654–1902 | 8 | 27 | 31 | 69 | 8 | 77 | 33 |
| East of divide | 10,846 | 1654–1915 | 14 | 13 | 17 | 76 | 1 | 77 | 22 |
| Total | 27,542 | 1654–1915 | 19 | 11 | 15 | 68 | 1 | 69 | 19 |

NI, number of fire intervals; WMPI, Weibull median probability interval; MFI, mean fire return interval; Min, minimum; Max, maximum; SD, standard deviation.

182 years, shorter than the rotations found in the present study. However, their results were strongly influenced by a single fire event around 1680 that burned more than 80% of the 3241 ha study area. On the other hand, mean fire intervals are similar between the Medicine Bow study and the sub-areas of the east side of the divide in the current study (31 vs. 26 and 41 years).

In our study area the number of large fire years increases during the second half of the nineteenth century following a relative hiatus from 1783 to 1850. The increase is particularly

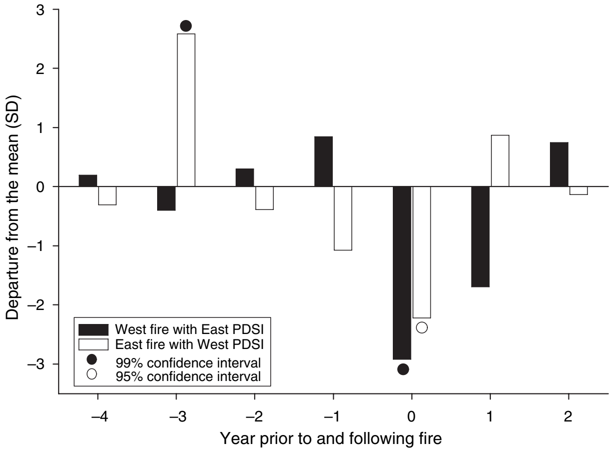


**Figure 7** Superposed epoch analysis showing departures (in standard deviations) from mean reconstructed values of the Palmer drought severity index (PDSI; Cook *et al.*, 1999) for large fire years (> 100 ha in reconstructed landscape or > 50 ha in the present day landscape and at least two scars across a barrier to fire spread). Fire years on each side of the divide are analysed against PDSI from the opposite of the divide. PDSI is shown during the fire year (lag year 0), prior to the fire year (lags − 4 to − 1), and after the fire year (lags 1 and 2). Confidence intervals are derived from 1000 Monte Carlo simulations performed on the PDSI data set for 1650 to 1985.

marked on the eastern side of the divide. Similarly, in the northeastern sector of ROMO there is a marked increase in the occurrence of fire during the second half of the nineteenth century (Buechling & Baker, 2004). This pattern of few fires in the late eighteenth century to the 1840s followed by an increase in fire frequency in the mid- and late-nineteenth century is widespread in the southern Rockies and the southwest and coincides both with permanent Euro-American settlement and climatic variation favourable to fire. The period of low fire occurrence in ponderosa pine and Douglas fir forests in the southern Rockies and southwest has been related to reduced year-to-year variability in moisture variability linked to reduced amplitude of the El Niño–Southern Oscillation (Swetnam & Betancourt, 1998; Veblen *et al.*, 2000; Donnegan *et al.*, 2001; Kitzberger *et al.*, 2001). Recent research demonstrates that the period of low fire occurrence in the subalpine forests in our study area is also associated with reduced drought severity linked to a prolonged cool phase of the Atlantic Multidecadal Oscillation (Sibold & Veblen, inpress). During the period of increased fire, the coincidence of more frequent and severe drought with Euro-American settlement makes it difficult to separate the contributions of these two potential explanations for increased occurrence of fire. Certainly, the spread of the extensive fires in the late nineteenth century was dependent on weather favourable to the spread of fire. However, the greater increase in occurrence of fire on the eastern side of the divide is also consistent with the greater presence of Euro-Americans in this area (Buchholtz, 1983).

## Drivers of fire regimes at local, meso- and regional scales

Fire regimes in the ROMO study area are influenced by driving factors originating at local, meso- and regional scales. At the local scale, consistent differences in the proportions of the spruce–fir and lodgepole pine cover type represented by post-fire cohorts reflect local abiotic or biotic influences on fire regimes. A higher frequency of fire is associated with the lower elevations and more xeric topographic positions typical of the lodgepole pine cover type (Peet, 1981; Sibold, 2001). Large percentages of the spruce–fir cover type located at higher elevations and more mesic site conditions in each sub-area did not record evidence of any fire for > 400 years. In contrast, all of the lodgepole pine cover type originated following fires in the last 400 years. This is consistent with previously reported differences in fire history for forests dominated primarily by spruce–fir as opposed to forests containing a large component of lodgepole pine (Romme & Knight, 1981). Although amount of fuel generally does not limit the occurrence of fire in subalpine forests in the Rockies (Baker, 2003), the dry fuel conditions necessary for the spread of fire appear to occur more frequently in the lodgepole pine cover type than in the spruce–fir cover type.

At a mesoscale, fire regimes were similar for sub-areas on the same side of the divide but contrasted among sub-areas on opposite sides of the continental divide. Sub-areas on the east side of the divide had more frequent and smaller fires in comparison to the sub-areas on the west side of the divide. Such differences may reflect differences in meso-scale climate or in the surrounding vegetation patterns on the west vs. the east side of ROMO. In the northern Front Range, the west side of the divide tends to have greater annual precipitation (Kittel *et al.*, 2002), annual snowpack is less variable and persists longer into late spring (Changnon *et al.*, 1991) and strong, drying Chinook winds are rare or absent (Barry, 1992). These meso-scale climatic differences contribute to more frequent and/or more severe desiccation of fuels in the subalpine forests on the east side of the continental divide.

In addition to favourable fire weather being more frequent on the east side of the divide, the juxtaposition of the subalpine forests with more flammable montane forests on the east side may contribute to these meso-scale differences in the fire regime. On the west side of the divide, subalpine forests border Grand Lake and dry park vegetation of scattered shrubs and grasses that may inhibit the ignition and/or spread of fire due to low continuity of fuels. In contrast, subalpine forests on the east side of the divide border upper montane forests of ponderosa pine and Douglas fir (see Study area), and some fires that ignite in the montane zone may spread upslope into the study area of subalpine forests. In fact, years of large fires on the east side of the study area are synchronous with years of widespread fire (two or more trees scarred in two or more of 41 fire history sample areas; Veblen *et al.*, 2000) in the montane zone ($\chi^2 = 42.04$; $P < 0.005$). During the nineteenth century period of settlement and mining activity, increased anthropogenic ignitions on the east side (Buchholtz, 1983; Veblen & Lorenz, 1991) may also have been a contributing factor, but the pattern of more frequent fires on the east side also is typical of the period prior to Euro-American settlement (Fig. 5). Irrespective of the mechanism, the meso-scale variations in the fire regime have resulted in somewhat contrasting subalpine landscapes in which forest patches are smaller and younger on the east side in comparison to the west side of the divide.

A strong regional climatic influence on the fire regimes in the study area is reflected by synchrony of large fire years and similar centennial-scale fire patterns on both sides of the divide. Each side is characterized by the fire-free period from the late eighteenth to mid-nineteenth centuries followed by increased fire in the late nineteenth century. Furthermore, large fire years on each side of the divide in ROMO are associated with regional-scale dry conditions inferred from tree-ring proxy records (PDSI) from the opposite side of the divide. Regional-scale drought during the year of fire occurrence is highly conducive to the occurrence of fire in the subalpine forests of ROMO (Fig. 7). Such drought conditions are statistically associated with the positive phase of the Southern Oscillation (La Niña) which has previously been associated with the occurrence of fire in montane and subalpine forests in the Front Range (Veblen *et al.*, 2000; Donnegan *et al.*, 2001; Sherriff *et al.*, 2001). On the east side of the study area, years of large fires tend to lag above average moisture by 3 years but there is no lagging pattern on the west side. This lagged association of fire with above-average moisture appears to be a neighbourhood effect of the bordering montane forests of Douglas fir and ponderosa pine. In the nearby montane forests, years of widespread fire also tend to occur 3 years after above-average spring moisture, which is statistically associated with the negative phase of the Southern Oscillation (El Niño; Veblen *et al.*, 2000). In the montane zone of xeric forests this lagged response to increases in moisture is interpreted to be the result of increased production of fine fuels (Veblen *et al.*, 2000). Because fires in the subalpine forests are not limited by lack of fuel (Baker, 2003) and this lagged pattern is found only on the east side of the divide, it is likely that the 3-year lagging of wet years by large fire years is due to the spread of fires upslope from the neighbouring montane forests. The relationship of the occurrence of fire in ROMO subalpine forests to broad-scale circulation anomalies such as the El Niño–Southern Oscillation, the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation is the subject of a separate analysis (Sibold & Veblen, inpress).

Climatic variability is arguably the primary driver of the fire regime in the study area; however, influences at the local and meso-scales are also important in shaping the fire regime and resulting landscape patterns. Local-scale differences in cover type and site conditions allow the same regional synoptic climatic patterns to differentially affect the probability of occurrence and/or spread of fire in lodgepole pine vs. spruce–fir forests. Meso-scale differences in climate appear to increase the probability of favourable fire weather on the east side of the divide. And the proximity of subalpine forests to more flammable montane forests also increases the likelihood of the spread of fire on the east side. Thus, despite the probable dominance of climate as the primary driver of the subalpine fire regime, interactions with local- and meso-scale drivers increases stand- and landscape-scale variations in forest patterns. In contrast, regional-scale climatic influences tend to decrease the heterogeneity of the fire regimes across the divide and result in large areas on both sides of the divide being in similar stages of post-fire development. Such an interpretation of the relative importance of potential driving factors of fire regimes incorporates both a top-down and a bottom-up perspective on the driving factors of ecosystem processes (Levin, 1992; Lertzman & Fall, 1998; Heyerdahl *et al.*, 2001).

## Management implications

The fire history of the subalpine forests of ROMO clearly is not consistent with the key premises underlying much of the current policy of fire management and ecological restoration in the forests of the western USA (US Government, 2002; USDA, 2002). These premises include a widespread notion among decision-makers, managers and the general public that in general suppression of formerly frequent surface fires in the western USA has resulted in increases in stand densities, increased susceptibility of forest to outbreaks of pests and pathogens, and a shift in the severity of fire from non-lethal surface fires to stand-replacing fires. This general scenario, which is so prominent in policy discussions, is referred to as the fire exclusion/fuel build-up model (Veblen, 2003b). The premises behind this model need to be critically evaluated for different forest ecosystem types and even for different geographical areas within the same ecosystem type (Veblen, 2003b; Schoennagel *et al.*, 2004). In the subalpine forests of ROMO, in contrast to a key premise of the fire exclusion/fuel build-up model, surface fires did not play a significant role in the historical fire regime. Instead, the historical fire regime was characterized by infrequent and large stand-replacing fires associated with strong droughts. Elsewhere in other ecosystem types it may be valid to interpret the currently high stand densities as a consequence of reduced fire frequency during the twentieth century (e.g. in ponderosa pine ecosystems of Arizona; Allen *et al.*, 2002). However, in the case of subalpine forests in ROMO, high stand densities are entirely consistent with the historical fire regime of stand-replacing events. The high stand densities in relatively young lodgepole pine stands (i.e. < 150 years) in the present landscape of northern Colorado (Moir, 1969; Peet, 1981) reflect the effects of widespread burning in the nineteenth century, and it is highly likely that similarly high densities followed large fire events in the 17th and 18th centuries.

Given the long fire-free intervals in each watershed prior to the early 1900s, fire suppression does not appear to have created unnaturally low amounts of burning nor unnatural landscapes in the subalpine forests of ROMO. Thus, current forest conditions should not be considered outside of the historical range of variability typical of the past four centuries. Although current forest conditions in the subalpine zone of ROMO are within the historical range of variability of this temporally highly variable landscape, it is likely that fire suppression has stopped some natural fires from burning larger areas during the twentieth century. For example, for the period 1920 to 1989, PDSI values were below (i.e. drier) those associated with widespread fire during the historical fire regimes on the west and east sides of the divide by 13 and 17 times, respectively. Given the uncertainty that future suppression activities will continue to prevent large fires, managers should plan for future fire events that burn large percentages of the park in single events. The public should be aware that such large and severe fires are a natural part of the historical fire regime and that they are likely to occur again. Conversely, if managers assume continued success at preventing large fires, resource planners must expect increasingly large areas of old forest that are more susceptible to both insect outbreaks (Veblen *et al.*, 1994; Kulakowski *et al.*, 2003) and to blow-down (Veblen *et al.*, 1991; Kulakowski & Veblen, 2002).

The infrequent nature and high temporal variability of the occurrence of fire in subalpine forests in ROMO prior to Euro-American settlement suggests that neither the low amounts of burning during the twentieth century nor any anthropogenic contribution to increased burning during the nineteenth-century settlement period resulted in modern forest conditions outside of the historical range of variability. In the light of these findings, thinning of forest to restore forest conditions inferred for a former frequent surface fire regime is clearly inappropriate. Furthermore, the logic of thinning for the purpose of reducing fire hazard, regardless of whether it constitutes ecological restoration, is questionable from the perspective of what magnitude of thinning would be required to significantly alter fire behaviour during extreme fire weather as well as from the perspective of its impact on other resource values (e.g. wildlife, aesthetics). Perhaps limited resources for mitigation of the fire hazard are better directed at public education, planning for future expected fires and their aftermath, and potentially at fuel type conversion in the proximity of structures or other high-value features such as reservoirs. Although such decisions on how best to mitigate fire hazards in the subalpine zone are beyond the scope of the present paper, we stress that knowledge of the historical fire regimes in the subalpine zone of ROMO does not support the widespread notion that extensive forest thinning would return fuel conditions to a more natural state.

This study illustrates that within the subalpine forest zone of the Colorado Rocky Mountains there is a significant amount of variation in fire regimes according to local site factors (integrated by forest cover type), and at a meso-scale in relation to climatic gradients and the ecological effects of neighbouring non-subalpine vegetation. These local- and meso-scale sources of variation should be a source of caution in the acceptance of generalizations about fire regimes at broad spatial scales such as for the entire subalpine zone of ROMO. Furthermore, the meso-scale variations in fire regimes exhibited in this study reinforce the notion that information on fire history is highly area-specific even within the same broad forest ecosystem type (Landres *et al.*, 1999; Veblen, 2003a). Any extrapolations of information about the fire regime for a particular cover type should be treated as hypotheses to be evaluated by collection of data on the history of fire in the target area.

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## REFERENCES

Allen, C.D., Savage, M., Falk, D.A., Suckling, K.F., Swetnam, T.W., Schulke, T., Stacey, P.B., Morgan, P., Hoffman, M. & Klingel, J.T. (2002) Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications*, **12,** 1418–1433.

Arno, S.F. (1980) Forest fire history in the northern Rockies. *Journal of Forestry*, **8,** 460–465.

Arno, S.F. & Sneck, K.M. (1977) *A method for determining fire history in coniferous forests of the mountain west.* US Department of Agriculture Forest Service General Technical Report INT-42, Ogden, UT.

Baker, W.L. (2003) Fires and climate in forested landscape in the U.S. Rocky Mountains. *Fire and climatic change in temperate ecosystems of the western Americas* (ed. by T.T. Veblen, W.L. Baker, G. Montenegro and T.W. Swetnam), pp. 120–157. Springer, New York.

Baker, W.L. & Kipfmueller, K.F. (2001) Spatial ecology of pre-EuroAmerican firs in a Southern Rocky Mountain subalpine forest landscape. *Professional Geographer*, **2,** 248–262.

Barry, R.G. (1992) *Mountain weather and climate*. Routledge, New York.

Bessie, W.C. & Johnson, E.A. (1995) The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology*, **3,** 747–762.

Buchholtz, C.W. (1983) *Rocky Mountain National Park: a history*. Colorado Associated University Press, Boulder, CO.

Buechling, A. & Baker, W.L. (2004) A fire history from tree rings in a high elevation forest of Rocky Mountain National Park. *Canadian Journal of Forest Research*, **34,** 1259–1273.

Changnon, D., McKee, T.B. & Doesken, N.L. (1991) Hydroclimatic variability in the Rocky Mountains. *Water Resources Bulletin*, **5,** 733–743.

Colorado Climate Center (2002) Allenspark and Grand Lake monthly summaries for years 1944–1993. http://ulysses.atmos.colostate.edu/.

Cook, E.R., Meko, D.M., Stahle, D.W. & Cleaveland, M.K. (1999) Reconstruction of past drought across the coterminous United States from a network of climatically sensitive tree-ring data. *Journal of Climate*, **12,** 1145–1162.

Despain, D.G. (1991) *Yellowstone vegetation: consequences of environment and history*. Roberts Rinehart Publishing Co., Boulder, CO.

Donnegan, J.A., Veblen, T.T. & Sibold, J.S. (2001) Climatic and human influences on fire history in Pike National Forest, central Colorado. *Canadian Journal of Forest Research*, **9,** 1526–1539.

Duncan, R.P. (1989) An evaluation of errors in tree age estimates based on increment cores in Kahikatea. *New Zealand Natural Sciences*, **16,** 31.

Graybill, D.A. *International tree-ring data bank*. IGBP PAGES/World Data Center for Paleoclimatology, NOAA/NGDC Paleoclimatology Program, Boulder, CO.

Grissino-Mayer, H.D. (1995) Tree-ring reconstructions of climate and fire history at El Malpaís National Monument, New Mexico. PhD Dissertation, University of Arizona, Tucson, AZ.

Gutsell, S.L. & Johnson, E.A (1996) How fire scars are formed: coupling a disturbance process to its ecological effect. *Canadian Journal of Forest Research*, **26,** 166–174.

Heinselman, M.L. (1973) Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Quaternary Research*, **3,** 329–382.

Hess, C. (1993) *Rocky Times in Rocky Mountain National Park: an unnatural history*. University of Colorado Press, Boulder, CO.

Heyerdahl, E.K., Brubaker, L.B. & Agee, J.K. (2001) Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. *Ecology*, **3,** 660–678.

Holmes, R.L. (1983) Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*, **43,** 69.

Huckaby, L.S. & Moir, W.H. (1995) Fire history of subalpine forests at Fraser Experimental Forest, Colorado. *Proceedings of the symposium on fire in wilderness and park management* (ed. by J.K. Brown, R.W. Mutch, C.W. Spoon and R.H. Wakimoto), pp. 205–210. US Department of Agriculture, Forest Service General Technical Report INT-GTR-320, Intermountain Forest and Range Experiment Station, Ogden, UT.

Johnson, E.A. & Gutsell, S.L. (1994) Fire frequency models, methods and interpretations. *Advances in Ecological Research*, **25,** 239–287.

Kipfmueller, K.F. & Baker, W.L. (2000) A fire history of a subalpine forest in south-eastern Wyoming, USA. *Journal of Biogeography*, **1,** 71–85.

Kittel, T.G.F., Thornton, P.E., Royle, J.A. & Chase, T.N. (2002) Climates of the Rocky Mountains: historical and future patterns. *Rocky Mountain futures: an ecological perspective* (ed. by J. Baron), pp. 59–82. Island Press, Covelo, CA.

Kitzberger, T., Swetnam, T.W. & Veblen, T.T. (2001) Inter-hemispheric synchrony of forest fires and El Niño-Southern Oscillation. *Global Ecology and Biogeography*, **10,** 315–326.

Kulakowski, D. & Veblen, T.T. (2002) Subalpine forest development following a blowdown in the Mount Zirkel Wilderness, Colorado. *Journal of Vegetation Science*, **14,** 653–660.

Kulakowski, D., Veblen, T.T. & Bebi, P. (2003) Effects of fire and spruce beetle outbreak legacies on the disturbance regime of a subalpine forest in Colorado. *Journal of Biogeography*, **9,** 1445–1456.

Landres, P., Morgan, P. & Swanson, F. (1999) Overview of the use of natural variability concepts in managing ecological systems. *Ecological Applications*, **9,** 1179–1188.

Lertzman, K. & Fall, J. (1998) From forest stands to landscapes: spatial scales and the role of disturbances. *Ecological scale* (ed. by D.L. Peterson and V.T. Parker), pp. 339–367. Columbia University Press, New York.

Levin, S.A. (1992) The problem of scale in ecology. *Ecology*, **73,** 1943–1967.

Loope, L.L. & Gruell, G.E. (1973) The ecological role of fire in the Jackson Hole area, northwestern Wyoming. *Quaternary Research*, **3,** 425.

Lorimer, C.G. (1985) Methodological considerations in the analysis of forest disturbance history. *Canadian Journal of Forest Research*, **15,** 200–213.

McNicoll, C.H. & Hann, W.J. (2004) Multi-scale planning and implementation to restore fire adapted ecosystems, and reduce risk to the urban/wildland interface in the Box Creek watershed. *Tall Timbers 22nd Fire Ecology Conference on 'Fire in temperate, boreal and montane ecosystems', Alberta, Canada, October 14–18, 2001*, pp. 294–316. Tall Timbers Research Station, Tallahassee, FL.

Minnich, R.A., Vizcaino, E.F., Sosaramirez, J. & Chou, Y.H. (1993) Lightning detection rates and wildland fire in the mountains of northern Baja-California, Mexico. *Atmosfera*, **6,** 235–253.

Moir, W.H. (1969) The lodgepole pine zone in Colorado. *American Midland Naturalist*, **81,** 87–98.

Peet, R.K. (1981) Forest vegetation of the Colorado Front Range. *Vegetatio*, **43,** 131–140.

Peet, R.K. (2000) Forests of the Rocky Mountains. *North American terrestrial vegetation*, 2nd edn (ed. by M.G. Barbour and W.D. Billings), pp. 75–122. Cambridge University Press, New York.

Renkin, R.A. & Despain, D.G. (1992) Fuel moisture, forest type and lightning-caused fire in Yellowstone National Park. *Canadian Journal of Forest Research*, **22,** 37–45.

Rocky Mountain National Park GIS (1995) *Covertypes of Rocky Mountain National Park* (ed. by Rocky Mountain National

Park GIS Program). Rocky Mountain National Park, Estes Park, CO.

Romme, W.H. (1982) Fire and landscape diversity in Yellowstone National Park. *Ecological Monographs*, **52,** 199–221.

Romme, W.H. & Despain, D.G. (1989) Historical perspective on the Yellowstone fires of 1988. *BioScience*, **39,** 695–699.

Romme, W.H. & Knight, D.H. (1981) Fire frequency and subalpine forest succession along a topographic gradient in Wyoming. *Ecology*, **62,** 319–326.

Schoennagel, T.L., Veblen, T.T. & Romme, W.H. (2004) The interaction of fire, fuels and climate across Rocky Mountain forests. *BioScience*, **54,** 661–676.

Sherriff, R.L., Veblen, T.T. & Sibold, J.S. (2001) Fire history in high elevation subalpine forests in the Colorado Front Range. *Ecoscience*, **3,** 369–380.

Sibold, J.S. (2001) *The forest fire regime of an upper montane and subalpine forest, Wild Basin, Rocky Mountain National Park*. Master's Thesis, University of Colorado, Boulder, CO.

Sibold, J.S. & Veblen, T.T. (in press) Relationships of subalpine forest fires in the Colorado Front Range to interannual and multi-decadal scale climatic variation. *Journal of Biogeography*.

Stokes, M.A. & Smiley, T.L. (1968) *An introduction to tree-ring dating*. University of Chicago Press, Chicago, IL.

Swetnam, T.W. & Baisan, C.H. (1996) Historical fire regime patterns in the southwestern United States since AD 1700. Fire effects in southwestern forests. *Proceedings of the second La Mesa fire symposium* (ed. by C.D. Allen), USDA Forest Service General Technical Report RM-GTR-286, pp. 11–32. USDA Forest Service, Los Alamos, NM.

Swetnam, T.W. & Betancourt, J.L. (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate*, **11,** 3128–3147.

Turner, M.G. & Romme, W.H. (1994) Landscape dynamics in crown fire ecosystems. *Landscape Ecology*, **1,** 59–77.

Turner, M.G., Hargrove, W.W., Gardner, R.H. & Romme, W.H. (1994) Effects of fire on landscape heterogeneity in Yellowstone National Park, Wyoming. *Journal of Vegetation Science*, **5,** 731–742.

US Government (2002) Healthy forests: an initiative for wildfire prevention and stronger communities (online: http://www.whitehouse.gov/infocus/healthyforests/Healthy_Forests_v2.pdf).

USDA (2002) A collaborative approach for reducing wildland fire risks to communities and the environment: 10-year comprehensive strategy (online: http://www.fireplan.gov).

Van Wagner, C.E. (1978) Age-class distribution and the forest fire cycle. *Canadian Journal of Forest Research*, **8,** 220–227.

Veblen, T.T. (2000) Disturbance patterns in southern Rocky Mountain forests. *Forest fragmentation in the Southern Rocky Mountains* (ed. by R.L. Knight, F.W. Smith, S.W. Buskirk, W.H. Romme and W.L. Baker), pp. 31–54. Colorado University Press, Boulder, CO.

Veblen, T.T. (2003a) Historic range of variability of mountain forest ecosystems: concepts and applications. *Forestry Chronicle*, **2,** 223–226.

Veblen, T.T. (2003b) Key issues in fire regime research for fuels management and ecological restoration. *Fire, fuel treatments and ecological restoration: conference proceedings; 16–18 April, 2002, Fort Collins, CO* (ed. by P. Omi and L. Joyce), pp. 259–276. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Veblen, T.T. & Lorenz, D.C. (1991) *The Colorado Front Range: a century of ecological change*. University of Utah Press, Salt Lake City, UT.

Veblen, T.T., Hadley, K.S., Reid, M.S. & Rebertus, A.J. (1989) Blowdown and stand development in a Colorado subalpine forest. *Canadian Journal of Forest Research*, **19,** 1218–1225.

Veblen, T.T., Hadley, K.S. & Reid, M.S. (1991) Disturbance and stand development of a Colorado subalpine forest. *Journal of Biogeography*, **18,** 707–716.

Veblen, T.T., Hadley, K.S., Nel, E.M., Kitzberger, T., Reid, M.S. & Villalba, R. (1994) Disturbance regime and disturbance interactions in a Rocky Mountain subalpine forest. *Journal of Ecology*, **82,** 125–135.

Veblen, T.T., Kitzberger, T. & Donnegan, J. (2000) Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecological Applications*, **4,** 1178–1195.

Wadleigh, L. & Jenkins, M.J. (1996) Fire frequency and the vegetative mosaic of a spruce-fir forest in northern Utah. *Great Basin Naturalist*, **56,** 28–39.

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