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Research Report to the Boulder Mountain Parks Division of the Parks and Recreation Department, the City of Boulder Open Space Department, and the Wildland Fire Division of the Boulder Fire Department

USING A PLOT-TRANSECT METHOD TO DETERMINE THE HISTORICAL FIRE REGIME FOR THE MONTANE FORESTS OF BOULDER, COLORADO

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PART I

INTRODUCTION

The City of Boulder public forests, as part of the Colorado Front Range continuum, evolved within the context of a high-frequency fire disturbance regime (Veblen et al. 1996, Goldblum and Veblen 1992). In Front Range ponderosa pine (*Pinus ponderosa*) and Douglas-fir *(Pseudotsuga menzisii*) forests, frequent low-intensity surface fires are documented in tree ring records, preserved sedimentation layers, and are inferred through comparisons with early settler documentation of historical forest conditions (Veblen and Lorenz 1991). Studies have shown that non-lethal understory fires in these forests occurred an average of every 5 to 12 years in the Inland West before the influx of Euro-American settlement around 1858 (Swetnam and Betancourt 1990, Veblen and Lorenz 1991, Goldblum and Veblen 1992). Throughout much of the western US, Euro-American settlement corresponds to a dramatic increase in fire frequencies. Some, but not all, fire chronologies in the Boulder area have documented such a change (Goldblum and Veblen 1992, Veblen et al. *in press*), while an increase in fires in the late 1800s has been noted by historians (Veblen and Lorenz 1991, Smith 1981) and will likely emerge in subsequent fire history analyses in the western US.

As the Euro-American population in Boulder exploded in the early 1900's, forest fires were suppressed in order to protect land holdings, mining interests, timber investments, and the population. Suppression of all fires, whether anthropogenic or lightning ignited, has remained the dominant paradigm in forest management for nearly 100 years. Its ecological repercussions are being increasingly recognized as threats to the health and sustainability of many western forests (Covington et al. 1994).

Changes in structural and compositional characteristics of western ponderosa pine-Douglas-fir ecosystems as a result of fire suppression are well documented (Weaver 1951, City of Boulder 1999, 1960, Biswell et al. 1973, Covington and Moore 1994). Increased density of overstory trees and suppressed, slow-growing sapling-size trees are common changes in western forests since the initiation of fire suppression. Shade-tolerant species are at a competitive advantage now, whereas the fire-adapted shade-intolerant species are losing their dominance and their fire tolerance is no longer an advantage over their competitors (City of Boulder 1999, Covington and Moore 1994).

Many ecologists support the restoration or simulation of historical disturbance patterns in fire-suppressed forests through the application of prescribed burning or prescribed natural fire (e.g. Sackett 1975, Harrington and Sackett 1990, Brown and Sieg 1996, Arno et al. 1995). These applications are based on mean fire return intervals determined using fire history methods developed in the late 1970's (McBride and Laven 1976, Arno and Sneck 1977). Yet the application of such restoration practices does not often reflect a thorough site-specific knowledge of the historical patterning of fires across environmental gradients (City of Boulder 1999, Taylor and Skinner 1998). Fire histories usually cover limited, disconnected areas and sampling procedures have not been standardized for sample size, tree selection criteria, or heterogeneity of environmental features (Johnson and Gutsell 1994, McBride 1983).

Fuel conditions, tree diameter and species composition, disturbance and anthropological history, and topography are all thought to play a role in fire scar occurrence and historical fire patterns (Gill 1974, Hadley 1994, Tunstall et al. 1976), supporting the necessity for interpretation of fire patterns in relation to these and other environmental features (McBride 1983, Taylor and Skinner 1998). In order to sample for such features, a methodology which encompasses the topographic, vegetative, and historical diversity of the study site must be employed. In virtually every fire history study in the local area and throughout the western US, sample plots are variable in size or lack any definition of area, precluding the possibility for statistical comparisons between plots. Their location within the landscape of interest is not systematic or randomized, but instead involves sampling only subjectively selected trees within older cohorts to achieve a maximum record of historical fire events (Goldblum and Veblen 1992, Laven et al. 1980, Swetnam and Baisan 1996, Taylor and Skinner 1998, Veblen et al. 1996).

Few studies have addressed the need for proper sizing and stratification of the sampling area used to establish fire histories (Arno and Petersen 1983, Johnson and Gutsell 1994). Nor have studies analyzed the relative accuracy of fire history reconstructions determined from various sampling approaches, although some authors stress the importance of such analyses to the proper interpretation of fire history information as a basis for sound management decisions (Attiwill 1994, Johnson and Gutsell 1994, McBride 1983, Mutch and Cook 1996). Statistical design may not be considered practical or efficient by some authors, while informal sampling is thought to fulfill the objective of obtaining the most complete inventory of past fire events (Swetnam and Baisan 1996). Yet the results of informal sampling are used as if they provided a valid quantitative estimate of not only historical fire frequency but spatial characteristics as well (Johnson and Gutsell 1994). The measures of historical fire patterns are extrapolated without quantified validation across topographic and vegetative boundaries, and are used as the blueprints from which fire managements plans are drafted. This lack of attention to a statistical sampling design renders it impossible to determine how accurate or precise the fire regime reconstructions are, and brings into question the comparison of different fire history studies (Johnson and Gutsell 1994).

In order to substantiate the responsible reintroduction of historical fire regimes to fire-adapted ecosystems, the usefulness of a standardized methodology for evaluating fire history at watershed, stand group (management area), stand, and plot scale will be explored. This study examines a standardized plot-transect sampling design used to determine the fire history for Boulder's Open Space and Mountain Parks forests. Wedges from fire-scarred material are extracted from plots and fire events are dated using standard dendrochronological and cross-dating techniques (Arno and Sneck 1977, Kilgore and Taylor 1979, McBride and Laven 1976, Stokes 1980).

Although fire patterns are not typically random across the landscape, the inclusion of a representative diversity of landscape features will allow this study to evaluate historical fires as they occurred in the Boulder public forests. Stands were delineated and chosen by the Open Space and Mountain Parks departments to represent the diversity of the forests across the entire landscape. While the selection of stands was not random, because all areas within the boundary of every stand have an equal chance of being sampled, this sample design is statistically valid and resembles a randomized sample (Johnson and Gutsell 1994).

The limitations of this sampling approach are comparable to the limitations of any randomized mensurative study. Whether or not the plots within a stand encompass fire scars is entirely up to chance, as the location of the plot is random. If smaller fires characterize the stand's fire regime, then it is possible that no plot location will correspond with a historical fire event. On the other hand, if the stand was influenced by widespread understory fires, plots have a greater chance of capturing fire scars within their boundaries. A high sampling density of plots helps to increase the chances of finding fire-scarred materials regardless of the fire regime characterizing the stand. In addition, the number of plots used to sample each stand is based on the variability of the basal area of that stand, which likely corresponds to the fire history of that forest. Although this methodology differs significantly from that used in other studies, descriptive fire interval statistics will be compared with results from fire histories already completed in sites near Boulder. This will provide an estimate of the comparability of this alternative sampling approach.

As this approach involves sampling from the entire diversity of the landscape, relationships between landscape characteristics such as aspect, elevation, and topographic position can be statistically compared to corresponding fire history data. In addition, the inventory and management units defined by Open Space and Mountain Parks agencies are identical to the stands used for this fire history analysis, allowing for specific information on fire history in each stand to be utilized in ecological analysis and decision-making. Interpretation of these fire records will test the ability of a systematic plot-transect method to capture the spatial patterning of historical fire events.

Recent reconstructions of Front Range historical fire patterns have shown that most landscapes were subjected to fire regimes of mixed severity and size (Veblen et al. *in press,* Brown et al. *in press)*. Given the extreme nature of the topography, Boulder's forests have both mesic, north-facing dense forests capable of supporting stand-replacing fires, as well as the open, park-like ponderosa pine stands of the more southerly exposures. To supply fire history information that truly describes Boulder's diverse landscape, the fire regimes of small areas, defined by topographic and vegetative features, must be explored (Veblen *in press*). Therefore, plot-level fire scar collection across the diversity of Boulder's forests is used in this study as the starting point for all analysis. Plot-level (sub-acre), stand-level (11-50 acres; composed of grouped plots), and management group level (over 50 acres; composed of grouped stands) fire intervals statistics will be used in the fire reconstruction for Boulder's public lands to correspond to a multi-scalar management approach. Although experimental, the method presented in this study is hypothesized to provide a basis for the analysis of the relationships between Boulder's fire history, human history, and its forest characteristics.

The ability of this method to capture historical fire regime information in relation to landscape features will be compared with other nearby studies when possible. The hypotheses are as follows:

- The plot-transect method of fire scar sampling will supply information about Boulder's fire history comparable to that resulting from traditional sampling methods.
- This method will allow for a statistical examination of the relationships between fire interval data and forest and landscape characteristics.

Literature Review

Studies of fire history in the Northern and Central Front Range area are limited. Published fire history inventories in Boulder County include those conducted or calculated by Laven et al. in 1980, Goldblum and Veblen in 1992, Veblen et al. in 1996, and Mast et al. in 1998. Veblen et al. (1996) reported mean fire return intervals ranging from 8-14 years in lower montane sites to 20-30 years at higher elevation sites in Boulder County forests. Laven et al. (1980) found mean fire return intervals in the Roosevelt National Forest ponderosa pine- Douglas-fir stands to vary according to aspect and between historical eras. Intervals between fire scars did not generally change with topographic position, although the small sample size limits the conclusions which can be drawn from this study. In the Fourmile Canyon northwest of Boulder Creek just outside the boundaries of Open Space or Mountain Parks (Figure 1), Goldblum and Veblen (1992) compared four fire dating methods and found wedge sampling to be the most precise indicator of historical fire occurrence. Using 67 subjectively selected fire-scarred trees, the authors found a mean fire return interval of 15.2 years over the entire range of fire dates. Mast et al. (1998) quantified age structures of lower ecotone forests extending from the lower montane zone into the grasslands east of Boulder. These age structures were compared to fire disturbance regimes to show that changes in disturbance frequency has increased the density and extent of ponderosa pine in the grassland ecotone.

Variations in regional climate have been linked with concurrent fire years from sites along the Front Range (Veblen et al. 1996). Although research is continuing, results thus far have shown that historical fire events corresponded to the El Nino/ Southern Oscillation (ENSO) climatic cycle (City of Boulder 1999). Fire occurrences decreased during and increased 1-3 years following El Nino events (Swetnam and Baisan 1996, Veblen et al. 1996). El Nino events, with higher rates of precipitation, are believed to increase fuel production and thereby stimulate growth of the fine fuel necessary to carry fire. In Swetnam and Baisan's 1996 regional analysis of fire history in the Southwest, patterns of synchronous fire events across hundreds of miles supports the overriding influence of climate on long-term fire patterns. Drought indices were used to reveal that significant 2-year lag relationships existed between fire years and climate (Swetnam and Baisan 1996). The effect of climate on fire cycles is increasingly evident, providing explanations for the synchrony of major fire years in the Boulder area with those throughout the Southwestern US.

Using the traditional method of subjective sampling of fire scarred trees, none of these studies were completed with a statistical sampling design. The extent of Open Space or Mountain Parks forest included in any of these studies is minimal, and is limited to the lower elevations of grassland-ecotone contained in the eastern perimeters of the public lands.

STUDY AREA

Geography, Geology, and Soils

Boulder is located along the Colorado Front Range of the Rocky Mountains, about 30 miles northwest of Denver. In north central Colorado, the Front Range extends from 150 km south of the Wyoming border southwards to Canon City, Colorado. The massif stands as the easternmost protrusion of the Rocky Mountains in the United States.

The physical template on which Boulder's public forests developed is, like most of the Front Range, composed of an acidic Precambrian intrusive rock core (Madole 1973). This core has subsequently been intruded by acidic Tertiary plutons, creating the granodiorite Boulder Creek granite. The sedimentary stone that forms Boulder's scenic Flatirons backdrop is the Fountain Formation, a Pennsylvanian arkose sandstone and conglomerate (Hogan 1993). Coarsely textured, highly variable, and shallow soils comprise the substrate for Boulder's forests. Steep topography and frequent disturbance events prevent the soil profile from maturing in many sites (Peet 1981). Four complexes have been mapped in Boulder Mountain Parks and Open Space: the Goldvale-Rock outcrop, the Fern Cliff-Allens Park Rock outcrop, The Baller stony sandy loam, and the Juget-Rock outcrop (USDA 1975). These complexes are dominated by Ustolls in the meadows and some drier slopes, Lithic Orthents where the bedrock surfaces, and Cryoboralfs in forests and cooler sites (Hogan 1993). Cryoboralf soils are widespread in the lower montane forest, where slightly acidic, rocky, thin and immature soil characteristics are common (Mast et al. 1998, Peet 1981).

Climate

The City of Boulder is positioned in the nook of a topographic arc opening to the east, which gathers storm systems and pulls them upslope. As the easternmost extension of the Rocky Mountains in the US, Boulder's mountains are provided greater precipitation than are surrounding areas (Hogan 1993). Annual precipitation is 18 inches (45 cm), peaking in April and May, with upslope storms prevalent in the spring and fall as air masses from the Gulf of Mexico rise up against the mountain front (Callahan 1986). From June to September, low precipitation and high temperatures instigate higher rates of historical fire occurrence (Veblen et al. *in press*). Winter months are characterized by Chinook winds: strong, dry and warm air masses which blow down into Boulder from the west. July is the warmest month at an average of 74° F/ 23° C, while January is the coldest (0° C/ 32° F). The season of frost-free days comprises more than one-third of the year (Callahan 1986). Mean annual temperature is 51° F (10.5° C).

Site Description

The study site encompasses the land holdings of two governmental agencies in Boulder, the City of Boulder Open Space Department and the Boulder Mountain Parks Division. Both land holdings are designed to conserve and promote biological diversity and sustainability of the montane forest type. Recognizing the need to protect the ecological value of the foothills forests as early as 1890, Boulder's population subsequently created a city tax in the mid- 1900's to maintain and acquire lands to be managed for preservation and limited timber supply. Boulder citizens thereby have a particular investment and interest in the preservation of the city lands.

The Open Space Department is responsible for managing around 8000 acres of forested land, including woodlands and the montane zone. The forests extend to the border of the urban population of Boulder towards the east, and up the foothills to the Mountain Parks boundary in the west. Some of the most rugged terrain of the Open Space forests is located above the canyon and small town of Eldorado Springs, just south of Boulder. Here, railways ran through tunnels servicing old mining sites and historic recreation centers, providing ample fire ignition sources from the construction and use of railroads during the late 1800s and early and mid-1900s (Veblen and Lorenz 1986).

The City of Boulder Mountain Park has been called the *sanctum sanctorum* of Boulder, serving as one of the last low-elevation refuges of montane forest in the Colorado Front Range (Hogan 1993). Broadly bounded by the Open Space lands to the east, north, and south, and the Roosevelt National Forest to the west, Mountain Parks comprises ca. 6000 acres of lower to upper montane forest and woodlands. Encompassing the Flatirons and numerous other precipitous crags and steep slopes, Mountain Parks is a favored recreation site for the local population. Boundaries between the two land management agencies is purely political, as the topographic features of the two holding groups merge and intermingle.

Although recreationists frequent both land holdings, camping is not permitted and all campfires are prohibited in all of Open Space and Mountain Parks forests. Today's fire ignitions in the Boulder public lands are therefore primarily lightning generated or accidental. Fire suppression has been in effect since the creation of these two public lands agencies.

Vegetation of Boulder's Montane Forests

The Front Range ecotonal forests of Boulder are located where the Great Plains meet the southern Rocky Mountains. The narrow strip of montane forest (elevation c. 1800 to 2700 m) is located in the 3-6.5 km-wide foothills of the Front Range. Like montane forests throughout the Front Range, they are a disturbance phenomena, a product of frequent fire events, wind blow-down damage, and insect attacks which create a mosaic of stand ages and species compositions (Peet 1981). Fire is considered the dominant disturbance agent, thought to have maintained the open pine woodlands in elevations below 2000 m, and a ponderosa pine- Douglas-fir mix in the upper montane zone.

Steep environmental gradients provide a diversity of habitats, resulting in a high biological diversity within montane forests (Hogan 1993, Peet 1981). South-facing slopes and the lower montane zone (c. 1800 to 2300 m) are characterized by ponderosa pine (*Pinus ponderosa*) dominance, with nearly equal presence of Douglas-fir (*Pseudotsuga menziesii*), and scattered Rocky Mountain juniper (*Sabina scopulorum*). In the lower- and middle montane zone, north-facing slopes, which are cooler and moister than the south-facing aspects, show a loss of ponderosa pine dominance to increased Douglas-fir density and infrequent juniper. Aspen (*Populus tremuloides*) can be found in moist patches of the upper montane forests (c. 2400 to 2700 m), along with stands of lodgepole pine (*Pinus contorta latifolia*) where stand-replacing fires are thought to have occurred. Infrequent whitebark pine (*Pinus lambertiana*) or limber pine (*Pinus flexilis*) individuals can be seen scattered along the ridges of the slopes; they accompany *Pinus contorta* in areas too xeric for other conifers (Veblen and Lorenz 1986). In the upper montane zone, Douglas-fir tends to succeed lodgepole pine, limber pine, and aspen, which are all often colonizers of burned or disturbed sites (Peet 1981).

Understory vegetation differs largely according to aspect and elevation. Herbaceous species on south-facing, lower montane slopes include kinnikinnik (*Arctostaphylos uva-ursi*), wax currant (*Ribes cereum*), spike fescue (*Leucopoa kingii*), and sun sedge (*Carex pensylvania heliophila*). Understory vegetation of north-facing slopes includes jamesia (*Jamesia americana*), Rocky Mountain maple (*Acer glabrum*), ninebark (*Physocarpus monogynus*), and Oregon grape (*Mahonia repens*).

At elevations below the montane zone, former grasslands have been recently (within the last ~70 years) invaded by ponderosa pine and Rocky Mt. juniper, extending the range of pine woodland from the montane zone into the grasslands, which continue across the Great Plains (Goldblum and Veblen 1992). Bordering the montane zone at the upper elevation limit is the subalpine zone (c. 2800 m), where subalpine fir (*Abies lasiocarpa)* and Engelmann spruce dominate (*Picea engelmannii*) on all aspects.

Results from the 1996-1999 Forest Inventory

The forest inventory conducted during the years of 1996 to 1998 provides extensive information about Boulder Open Space and Mountain Parks forest stands. The impacts of logging and Euro-American Settlement were most obvious in the lower montane zone of the Open Space lands (City of Boulder 1999). The majority of trees sampled in Open Space plots had diameters at breast height under18 inches and were under 120 years old (City of Boulder 1999). Both ponderosa pine and Douglas-fir establishment dates were greatest in the early 1900s, presumably at the commencement of fire suppression policies or due to stand-replacing fires set by mining prospectors. Boulder's oldest trees (c. 300 years) were found along ridgetops and growing along or within scree fields, largely in Mountain Parks stands or in the Eldorado Springs stands of Open Space, where the topography prevented reasonable timber extraction access. Most of the stands were overstocked with seedlings (trees with DBH less than 1" and height greater than 6") and saplings (trees 1 to 4.9 inches DBH) (City of Boulder 1999).

Results from the inventory inspired a pro-active, adaptive management plan to be set forth for the two agencies, including extensive prescriptions for stand thinning and prescribed burning. Stand characteristics on which some of these prescriptions are based are shown in Tables 1 and 2 (Appendix A). Basal area is high for most stands, along with numbers of seedlings per acre. Average radial growth rates were less in stands with greater percent canopy cover, with a strongly inverse relationship between plot density and basal area increments for both ponderosa pine and Douglas-fir (City of Boulder 1999). Infestations of dwarf mistletoe on ponderosa pine (*Arceuthobium vaginatum*) are ubiquitous, while some sign of mountain pine beetle (*Dendroctonous ponderosae)* was also documented. No significant forests with old-growth characteristics were identified in the more than 1000 plots surveyed (City of Boulder 1999). These forest characteristics are not only the ecological result of the alteration of disturbance regimes initiated at the turn of the century. They also reflect the history of anthropogenic influence in Boulder's forests over the last 300 or more years.

ANTHROPOLOGICAL HISTORY

Native American Influence—Pre-Settlement

A complex and important component of Boulder's fire history is the interactions of humans with the forest landscape. Although Boulder's historical fire regime is an ecological phenomenon, its source and characteristics are colored by a significant anthropogenic element. The furthest reaching documentation of Boulder's Pre-Settlement past suggests that the peoples native to the Front Range of Colorado had some effect on the disturbance regime and therefore the ecology of the grasslands and montane forests. The specific influence of Euro-American Settlement on Boulder's fire regime is more obvious and accessible, but the influence of the Native Americans is likely equally important to understanding Boulder's fire history.

The first Euro-Americans to explore the Front Range of Colorado were searching for gold, inspired by the disintegrating fervor of the over-tapped mineral deposits of California and early explorers' mentions of possible gold in the nearby Platte River (Smith 1981). But before they had a chance to sift the streams, they were met by roaming populations of Southern Arapahoe, Kiowa, Comanche, Cheyenne, and the mountain-dwelling Ute who would hunt along the Front Range during the winter. As documented by archeological research in nearby areas, Native Americans had a presence in the Boulder area as early as 8000 years ago (Husted 1965). According to archeological evidence as well as historical accounts documented by early explorers, native peoples set fires in all major geographic areas in the US, particularly in the Southwest (Pyne 1982, Stewart 1951). During the 1870's, John Wesley Powell led the USGS surveys of the Rocky Mountains, noting that:

> Everywhere throughout the Rocky Mountain region the explorer away from the

> beaten paths of civilization meets with great areas of dead forests...the mountaineer sees the heavens filled with clouds of smoke. In the main these fires are set by Indians (Stegner 1962).

The native stewardship of the land is believed to have included spring-season fires set mostly in the grassland-forest ecotone, where the treeless expanses of the Great Plains meet the lower elevation forests of the Rockies. Using fire not only for cooking and warmth, native peoples throughout the western US recognized the stimulatory effects of burning on grasses, reeds, and forage for game. This recognition is likely to have spawned series of arson in the grasslands and woodlands surrounding the Boulder area. A few short weeks following such fires, mule deer, elk, bison, and mountain sheep would flock to the new vegetation, and the natives would presumably usher them into groups to be killed for subsistence meat consumption and storage (Veblen and Lorenz 1991). Abundant game-drive fences further suggest that the hunting grounds around Boulder were important to the natives, and authors agree that controlled fires were likely used to drive game as described above (Veblen and Lorenz 1986).

Additional, yet less ecologically savvy uses of fire included intimidating settlers, driving away enemies or obscuring their vision, and communication between separated members of the same tribe. As noted by Captain John C. Fremont in Nevada in 1844;

> Columns of smoke rose over the country at scattered intervals—signals by which the Indians here, as elsewhere, communicate to each other that enemies are in the country. (Fremont 1887).

Such communication may have provided the ignition source for wildfires, or it may have instigated the setting of larger forest fires, if groups were separated by great distances and communication was essential (Gruell 1985). Unintentional expansion of the fire boundary may have ensued, given the proper fuel and climate conditions, causing widespread fires which could not be suppressed given the tools available at that time.

Lightning Vs. Native American Ignition Sources

The inability to differentiate between fires set by native peoples and those ignited by lightning complicates the Native American era of fire history analysis for locations along the Rocky Mountains and throughout the interior west. Implications for management depend upon whether or not the Native American-set fires significantly augmented the number of fires caused by lightning. In a fire history study compiling data from 63 sites throughout the Southwest, Swetnam and Baisan (1996) analyzed recent records of lightning strikes to conclude that even without Native American ignition sources, fire frequencies would have been accounted for by lightning ignitions in most cases. Their data support the hypothesis that proper fuel and climate conditions were more limiting than were ignition sources. Contrasting with popular belief, the authors conclude that "even if humans had never crossed the land bridge from Asia to North America, historical fire regimes in most Southwestern forests would still have been similar...to the fire regimes that we have documented" (Swetnam and Baisan 1996).

Yet archaeological identification of long-term Native American dwelling sites in Montana provided researchers with the opportunity to compare fire histories between known habitation sites and remote areas lacking any archeological evidence (Barrett 1980). Before 1860, substantial differences were found in the fire frequencies of paired sites (Barrett 1980). It is suggested that other locations known to have been inhabited by Native Americans—even if, as in Boulder's case, the inhabitants were nomadic-- were likewise significantly affected by intentional Native American burning (Barrett 1980, Gruell 1985).

Defining the historical range of variability of fire occurrence in Boulder thereby requires an acceptance of a lack of boundaries between lightning and anthropogenic fire ignition sources. The degree to which anthropogenic ignitions occurred throughout the last 8000 years has the power to redefine our concept of "natural" forest succession and the montane forest's composition. Without the tools to quantify this historical influence, scientists evaluating the historical disturbance regime for western forests stress the probable occurrence of Native American fires without quantifying the influence on the fire regime. Humans have inhabited the Boulder area throughout the extent of this fire history analysis. Their influence here will be considered a component of the "natural" fire regime by necessity.

Although the native peoples use of fire cannot be differentiated from natural ignitions, the marked increase in tree-ring documented fires in the late 1850's corresponds precisely to Euro-American settlement of the Boulder area.

Settlement: The Colorado Gold and Silver Mining Pursuits

Although French and Spanish explorers and fur traders probably visited the Front Range in the 1700's, the first documented presence of Euro-American settlers in the Boulder area was in 1858, although earlier presence is noted in historical literature (Smith 1981). Attempts by the Arapaho natives could not stop the entrepreneurial spirit of the pioneers, and gold was discovered in tributaries of Boulder Creek in 1858. Word of the discovery brought forth the prospectors, and by 1859 both the cities of Boulder and Denver were established (Veblen and Lorenz 1991). At its height, the Colorado Gold Rush beckoned as many as 100,000 prospectors to the dozens of boom towns that emerged in the early years of the Rush (Buccholtz 1983). Silver and tellurium discoveries followed, intensifying the need for development of wagon roads and later railroads (Veblen and Lorenz 1991). These roads followed Boulder Creek up Boulder Canyon and Left Hand Canyon, near present-day stands Fox-E, Fox-W, Kassler, and the 1- series of Mountain

Parks stands on Anemone Hill (Fig. 1). At the top of Left Hand Canyon, the mining settlement of Gold Hill was nearly deserted after a wildfire burned the town in October of 1860 (Smith 1981).

Influence of Settlement on Vegetation and Disturbance Patterns

Fire occurrence increased drastically during the Gold Rush years; at times a simple result of the practice of clearing "...away the fallen leaves so as to expose the naked rocks to the observation of the prospector" (Tice 1872). Other fires were accidental— escaped campfires and clearing of the forests for development in the area. Fire histories in nearby areas show a dramatic increase in fire scars during the settlement years (Veblen et al. 1996, Goldblum and Veblen 1992).

Within 20 years of the discovery of gold, the Union Pacific Railroad was constructed from Boulder westward into the mountains up Four Mile Canyon, again near the 1- series of Anemone Hill stands. Additional ore-transport tracks up the picturesque canyons attracted tourists, and hotel and spa sites were established. Eldorado Springs became a popular resort destination near the turn of the century, after railroads were constructed up the Eldorado Canyon and westward through the Rockies. This development, clearing of land, and influx of human population all provided potential sources of ignition for fires. The Eldo-N, S, E, and –W stands, along with the Mountains Parks 7- sites were all within the realm of influence of the population growth in the early 1900's. Fires were commonplace in the area during the 1870's through 1900. In 1871, 51 indictments for illegal fires were issued in Boulder County (Tice 1872). Around 1900, an estimated 11,700 hectares were burned in a wildfire southwest of the city of Boulder (Kemp 1960).

Demands for grazing lands and timber resources during the mining era were high. Ponderosa pine logging was common in Boulder's montane forests, and in some areas such as Boulder Canyon and Left Hand Canyon, timber removal was complete. The wood was used for building mines, for fuel, housing, and railroad construction. Loggers were reported to have set large fires in the 1890s in Colorado to salvage log the burned timber (Jack 1899). Logging continued to be important even after the formation of the Colorado Forest Reserve in 1910, which included much of Boulder County's montane forests. Active fire suppression was initiated in 1920, largely to protect the timber resources.

The Roosevelt National Forest engaged in logging and intensive grazing of both pine and Douglas-fir forests until the 1960's (Veblen and Lorenz 1991). Many of the sites included in this study had been selectively logged, especially in the lower elevation stands. Stumps from the settlement era provided some of the samples used to interpret the fire history of Boulder.

The influence of Euro-American settlement on Boulder County's forest vegetation can be seen in a time-lapse photographic analysis by Veblen and Lorenz (1991). The authors used the earliest known photographs from the region and found the present-day locations for exact comparisons. In general, the lower montane conifer zone has extended eastwards into the grasslands—a phenomenon thought to be the result of fire suppression or even climate change. Many grasslands documented in the photographs dating before 1900 are now populated by ponderosa pine and Rocky Mountain juniper. Similar phenomenon of conifer invasion of grasslands has been observed throughout the western US (Savage 1989, Vale 1981). These youngest stands within the management boundaries of Open Space were not included in this study, as the average stand ages are well below 90 years and well within the temporal grasp of fire suppression.

Also subject to fire suppression, the upper montane zone has increased in density and Douglas-fir presence. Many of the photographs from the late 1800s showed recently-burned stands throughout Boulder County. These fires are believed to have been ignited by settlers, either accidentally or intentionally. The present composition of the forest surrounding Boulder includes large patches of even-aged stands with origins dating back to the Euro-American settlement. Most of the historical photographs taken between 1880 and 1915 show stands in early stages of development, due to the fires or logging (Veblen and Lorenz 1991). The diversity of tree species in the historical photographs supports the belief that the montane forests of Boulder resulted from a variety of frequent disturbance events.

Presettlement forests were not uniformly old-growth or dominated by shade-tolerant species (Veblen and Lorenz 1991). Based on photographic comparisons, on xeric sites a shift in dominance from Douglas-fir to ponderosa pine following fire was seen, while at mesic sites Douglas-fir stands were replaced by Douglas-fir after disturbance events (Veblen and Lorenz 1991). Stand dominated by aspen in the historical photos have been replaced by conifers during the Fire Suppression period, while the lodgepole pine stands appear to have replaced themselves.

Reconstructions of stand age and size structures have been utilized in understanding the history of other southwestern ponderosa pine forests similar to those found in Boulder. Low-density, open-canopy forests have shifted during the last century to higher-density, smaller-diameter and closed-canopy stands (Covington and Moore 1994, Covington et al. 1997, Fule et al. 1997). Logging of larger-diameter trees also contributed to this shift in forest structure.

After the devastating northern Rockies fires of 1910, the enactment of the nation-wide fire suppression policy eventually exerted its effect in Boulder around 1920 (Veblen et al. 1996). Fire suppression helped support the influx of lower canopy trees and the increase in stand density in Boulder's forests, to the competitive detriment of the remaining older stand component (Biondi 1996, City of Boulder 1999). The change in forest structure associated with the increase in widespread burning during Euro-American Settlement resulted in such a low fuel load in the early 1900's that fires were further decreased (Veblen and Lorenz 1991). Without fire to "thin" the understory, small trees continue to thrive today in great densities, stressing the overstory for nutrients and water while providing "fuel ladders" which may increase the severity of potential fires. As fire has been prevented, the danger of severe damage to Boulder's forests and danger to its human population has been exacerbated.

Relationships between fire suppression and insect epidemics are less clear. The increase in tree density has likely increased competition in Boulder's forests over the last few decades. As mountain pine beetles (*Dendroctonous ponderosae*) are attracted to slow-growing, stressed trees, invasion potential is likely increased. High infestations of dwarf mistletoe further weakens trees and increases their susceptibility to insect attack (City of Boulder 1999, Veblen and Lorenz 1991). Greater densities of Douglas-fir in both the understory and overstory provide a greater food supply for the spruce budworm (*Choristoneura occidentalis)*. Tree ring studies have supplied some evidence that budworm epidemics have become more severe and frequent over the last few decades (Swetnam 1987). Because virtually no records of Pre-Settlement insect outbreaks exist, the actual effects of fire suppression on infestations is uncertain.

As in pine forests throughout the west, the historical and spatial patterning of fire through time has played a prominent role in the structure, health, and sustainability of Boulder's forests. This analysis of Boulder's fire history explores the fire disturbance regime and its spatial patterns through time to better understand one of the primary forces which molded the forests of the Front Range.

PART II.

METHODS

Open Space and Mountain Parks Forest Inventory

This study sampled a random selection of the Open Space and Mountain Parks forest inventory stands established between 1996 and 1998. Both Open Space and Mountain Parks inventory stands were delineated using aerial photography and field verification of homogenous overstory species composition and density patterns. Topographic features defined the parameters of the stands, such as abrupt changes in aspect, slope, elevation, or intersection with a drainage. When necessary, boundaries were defined by roads, fence lines, power lines, or property boundaries (Andrews et al. 2000). Stands were often bounded by riparian zones and encompassed an average of 25 acres (range 11 to 75 acres). Stands included some rocky outcrop features, but were generally bounded by larger features such as the Flatirons. Areas of especially heterogeneous forest were not included in the stand delineation, as the size of the groups would have been too small to sample appropriately.

Sampling intensity for the inventory was based on stand heterogeneity as reflected by basal area. This method assumed that all forest characteristics would be sufficiently sampled based on the variability of basal area (Andrews et al. 2000). The Colorado State Forest Service (1982) along with the Nature Conservancy (1996) provided the method used to determine the number of sample plots for each stand (Andrews et al. 2000). Based on a pre-sampled estimate of the mean number of trees with a minimum basal area (basal area factor of 20), an algorithm described in Andrews et al. 2000 (Forest Inventory Handbook) was used to determine the number of plots per stand. The sampling density should reflect the variability in basal area throughout the stand, as determined via pre-inventory sampling cruises. Each final plot encompassed an area of 1/10th acre located around a permanent monument or with permanent references.

All plots were located along transect lines perpendicular to the prominent slope angle. Minimum spacing of plots was two chains (132 feet) in order to prevent overlapped sampling of forest features. The first plot was typically located at the bottom of the slope at a standard of 2 chains within the boundary of the stand to ensure a starting point within the stand boundaries. The number of transect lines was estimated using the minimum required spacing between plots and the minimum spacing of 2 chains between transect lines. Transects were typically between 3 and 5 chains apart (Andrews et al. 2000).

Data gathered during the forest inventory included tree characteristics within a variable radius plot using a 20 BAF (basal area factor) prism. The first three trees within the variable radius plot were cored for age and the last 10-years of annual growth increment. Canopy cover was measured at set points around the plot center using a densiometer. Each seedling and sapling within 1/100th acre area around the plot center was recorded and the first from north was aged. Tables 1 and 2 describe some of the characteristics recorded during the inventory.

Fire History Study Stand Selection

Many of City of Boulder Open Space stands were treated during the early 1980s for a mountain pine beetle outbreak during the "Project Greenslope" forest treatment. Lower-elevation stands and open ponderosa pine stands were thinned and chemically treated to control the infestation and to lower the fire danger potential. Because these stands were in some cases heavily managed, and predominantly located at lower ecotone elevations, they were not included in this study's stand selection. They would have had to have been sampled and treated as a separate statistical group, a undertaking that was not deemed necessary due to time constraints.

Forty-one pre-delineated inventory stands encompassing 453 1/10th acre plots were included in this fire history study to reflect the heterogeneity of the landscape included in Boulder's public forests. After an initial elimination of those stands having recently undergone management prescriptions, each stand outside of the grassland/forest ecotone was sampled. With few exceptions, all delineated stands in the upper montane zone were sampled along the entire length of the north-south corridor of public lands (Figure 1). As Mountain Parks is responsible for managing more of the upper montane stands, the majority of samples were from this land management agency (25 vs. 14, Table 1). Lower montane zone stands were both from Open Space and Mountain Parks lands, although many of the low elevation Open Space stands were not sampled due to the complicating effects of recent management activities (e. g. Project Greenslope). Stands range from elevations of c. 5500 to 8000 feet, and areas of 7 to 50 hectares. Out of the 453 plots visited, 115 plots supplied fire-scarred materials for sampling. Table 2 describes stands with no fire scarred material in or near the sampled plots.

Sampling of Fire-Scarred Specimens

For each 1/10th acre plot visited, every fire-scarred live tree, stump, downed woody debris, or snag was sampled. Fire scars, generally triangular in shape and located at the base of the tree on the uphill side, were carefully identified, so as not to be confused with mechanical or animal damage (McBride 1983). Lightning scars were also sampled, as the date of the lightning scar might provide insight into the ignition source of a fire. Trees or remnant material with folded bark meeting at a vertical crease, suggesting a healed-over fire scar, were sampled. In all cases, these specimens yielded subtended fire scars.

Wedges samples, or partial cross-sections, were cut non-destructively from the fire-scarred portion of the specimens using a chainsaw, following methods established by McBride and Laven (1976) and further detailed by Arno and Sneck (1977). When compared to core sampling, this extraction technique allows for better identification and control of scar-related ring anomalies (Brown and Swetnam 1994, McBride 1983). Wedges were extracted at locations as close to the base of the tree or stump as possible in order to capture the maximum number of annual rings (Zackrisson 1980). The samples were prepared for ring analysis using standard methods; sanding the samples with consecutively finer grains of sand paper until a 400 grit smoothness was obtained for viewing under a dissecting microscope (Arno and Sneck 1977, McBride 1983).

Dating of Fire Scars

Ponderosa pine and Douglas-fir, the two tree species which provided all of the identifiable fire scar samples, are known to be amongst the most sensitive recorders of environmental characteristics. It was thereby concluded that cross-dating of the samples could be completed without using measurements of the ring widths for every sample. The cross-dating method is based on the premise that climatic influences have a dominant effect on the relative ring width patterns in trees within a localized area. A particularly rainy year in Boulder should therefore result in wider ring widths in most of Boulder's trees, while drought years result in narrower rings. The consecutive patterning of drought and high precipitation years creates a series of signatures which can be used to identify the precise date of a fire scar.

A selection of samples with longer records were scanned into the software WinDendro to measure ring widths and create an informal master skeleton plot chronology for this study; a procedure commonly used in fire history studies. For every fire-scarred wedge sample, the pattern of annual ring widths was skeleton plotted and cross-dated (Stokes 1980) with the informal master chronology and with formal tree-ring chronology data collected from sites along the Front Range (International Tree-Ring Databank; Drew 1974, Stokes and Smiley 1968). Locally absent, missing, or false rings were carefully detected using these comparative procedures, and scars with questionable sources were not included in the fire history reconstruction. Skeleton plotting provided a graphical methods of cross-dating ring width pattern signatures by identifying especially narrow or wide marker rings (Veblen et al. 1996). Combining the principles of skeleton plotting and cross-dating, precise dates were assigned to each year along the ring width axis (Veblen et al. 1996). Those samples lacking adequate marker years or patterns were not included in this study. Fire years which could not be conclusively cross-dated were dated within an error of + or – 5 years, and the results were analyzed separately from the verified fire dates. Around 60% of the samples cross-dated, while the ring patterns of the remaining samples were more sensitive to local environmental influences than to regional climate patterns, and could not thereby be dated using the patterns from the master chronology (Taylor and Skinner 1998). In addition, rot and decay rendered the conditions of other samples too denuded to date. A total of 205 samples were processed, of which 165 were datable using dendrochronological methods.

Fire-associated ring structures such as growth releases, double rings, traumatic resin ducts, or fire rings have been used as implications of fire events (Brown and Swetnam 1993). Such ring characteristics were not consistent enough in this study to be considered definitive markers of fire events, a conclusion commonly drawn in fire history studies in limited-site environments (e.g. Laven et al. 1980, Goldblum and Veblen 1992, Veblen et al. 1996, and Mast et al. 1998). Some structures were used to support the identification of a fire scar or its season, but fire dates were not obtained relying on even the most-prevalent traumatic resin ducts in order to avoid error.

Within the annual ring, the position of fire scars can be used to determine the season of the fire's occurrence. The shape, color appearance, and size of the cells which constitute the tree's annual ring, along with the scar shape can be viewed under a microscope for an analysis of scar seasonality (Dietrich and Swetnam 1984). Based on fire records of the last 80 years along the Front Range, fires occurred most frequently in late July or August. Yet differences in human ignition patterns or climatic cycles before the 1920's may have evoked an alternative seasonality pattern (Veblen et al. 1996). Such patterns may also lend insight into the ignition source of the fire, as lightning from thunderheads is most prevalent in the late summer, while Native Americans are believed to have set early-Spring burns (Pyne 1982, Stewart 1951).

Fire occurrences were delineated into one of six categories for the analysis of tree ring patterns: dormant season, earlywood, middle and late-earlywood (first, second, and third third of the earlywood), latewood, and unknown location (Grissino-Mayer 1995). Initiation of radial growth begins around late May in Boulder, and the growing season continues until mid-July or mid-August (Brown et al. *in press*). For intra-annual identification of a fire's seasonality within the tree ring, the dormant season scar is located between the annual growth rings, while the three consecutive earlywood season scar types are identified within the lighter-colored, larger-celled portion of the annual ring. Latewood scars appear within the dark band which is typically used to define the boundary of the ring—where cell walls are thicker and cells are smaller. Because many fire scar samples used in this study are characterized by extremely narrow rings, these estimates of intra-annual fire occurrences should be evaluated with caution. Each sample represents the particularities of a single tree, which may respond to environmental influences differently from even its closest neighbor (Veblen et al. 1996).

Seasonality is important in distinguishing the correct calendar year for a fire's occurrence. Because the dormant season in the Front Range runs from about September to April, identifying the location of the scar within the annual ring is important (Veblen et al. 1996). As described in Veblen et al. (1996), if a dormant season scar is found neighboring trees with latewood scars, the earlier year of the dormant season is assumed. If the dormant scar is accompanied by samples with early earlywood scars, then the later year is used for the scar's annual date.

Analysis of Fire Scar Data

The integrated computer software program for fire history analysis, FHX2, was used to analyze the fire history data (Grissino-Mayer 1995). This integrated software package includes features for analyzing historical fire patterns in relation to site characteristics (i.e. elevation or aspect), seasonality, or historical era. Here, fire dates for each plot was entered as a sample site to allow for the analysis of features associated with each plot, such as canopy cover, aspect, topographic position, or elevation. Use of the plot-transect sampling design lends itself to multiple-scale analysis. Fire regimes, fire scar occurrences, and the relationships of these data to topographic and vegetative characteristics were explored at the plot, stand, management group, and landscape or watershed scales.

The software package allows for the differential analysis of fire history using variations of sample group characteristics. For example, until a sample has been scarred once, it will not be considered a "recorder" tree until the year of that scar, as previously-scarred trees are known to be more susceptible to scarring by subsequent fires and are therefore more sensitive recorders (Romme 1980). The years included in the computation of descriptive fire interval statistics are thereby only equal to the recorder years. Although a sample may date back to the 1500s, its contribution to an area's fire history does not begin until the year of its first fire, which may be in the 1700s. This way, the influence of spot fires and lightning strikes is reduced, and the historical fire regime better reflects fire events which influenced areas outside the reach of a single specimen.

The differential analysis can also be programmed to include chronologies only from samples with a multiple number of fire scars. Due to the standardized sampling method used for this study, it is unlikely that adequate fire history information would be deemed using only multiple-scarred trees. The typical scarred sample had less than two fire scars, while the sample size within a plot was between 1 and 10 trees (Table 1). This fire regime analysis thereby shows the fire reconstruction using chronologies from specimens with at least one conclusive fire scar date. The program also allows the user to set a limit for the minimum percentages of trees scarred per site to be used in the analysis. Some fire histories in the area have limited their analysis to fires known to have scarred at least 25% and a minimum of two scars per tree or remnant material (Veblen et al. 1996), while other analyses using a smaller sample size included every fire from each scarred tree (Laven et al. 1980, Goldblum and Veblen 1992). Due to the random chance of capturing a fire scar in a plot, (about 25% likelihood for this study), all fire scars were included in the analysis while the minimum demarcation requiring at least 10% of the trees to be scarred per analysis group was utilized when possible and applicable (Grissino-Mayer 1995). Exceptions to these requirements of 1 fire scar per tree and a minimum of 10% of the trees scarred per analysis grouping are noted.

For each stand, graphical composite fire event charts were created (Appendix B; Grissino-Mayer 1995). These charts show the dates of fire occurrences in a graphic, chronological fashion. At the bottom of the graph is a composite master fire event chart (Dietrich 1980). This chart can be used to interpret the dates of all fire events for a given area. Here, the composite fire chronology is used for each stand as well as stands grouped according to landscape features or management areas. Because it is unlikely for a single tree to record every fire within an area, the composite fire chronology best describes the fire regime in Boulder's forests (Veblen et al. 1996).

Dates and seasons of fire scars were analyzed. Three different scales of analysis were applied to the data: the plot-level, the stand level, and the management zone level. Fire regimes were described and compared for various grouping of plots. Landscape characteristics, as well as historical time periods and seasonality, were compared with fire intervals using statistically-derived measures of central tendency.

Data Analysis

Historical Fire Regime

Models of fire history which attempt to translate ecological ideas into mathematics must be carefully applied, as the processes which dictate fire patterns through time are stochastic and measures of central tendency are based on numerous assumptions (Johnson and Van Wagner 1985). The traditional measure of central tendency in fire history analysis is the mean fire return interval (MFI). A measurement of the mean number of years between consecutive fires, the MFI can be calculated for any portion of a composite chronology (Dieterich 1980) or any group of fire composites for a given area. Baker (1992) highlighted the fact that the MFI for fire history analysis may not be an appropriate measure, as fire interval data is typically not symmetrically distributed. Because the maximum upper limit of the interval between fires is not defined whereas the lower limit is always 1, fire interval data is typically positively skewed (Baker 1992, Grissino-Mayer 1995). To help account for this positive skew, rings included in the analysis of fire intervals only include those after the sample's first fire event. Although the MFI assumes a normal distribution, a measure of central tendency which accounts for the skewedness in fire history data is the Weibull Median Probability Interval (WMPI) (Johnson and Gutsell 1994, Johnson and Van Wagner 1985).

Assumptions of the WMPI are that all the components of the area analyzed have been subjected to a homogenous fire regime for the time period of interest (Johnson and Van Wagner 1985). In Boulder's public lands, the fire regime is believed to have been relatively homogenous throughout the study area, as any stands subjected to prescribed burning were not included in the sample set. Yet the fire regime through time for the western US and Boulder has not been homogenous. The fire regime must therefore be separated into homogenous groups before the WMPI can be applied in the analysis of the entire dataset (Johnson and Van Wagner 1985).

Because the fire history record accumulated via this study does not date back further than the mid-1600s, four time period groupings are sufficient to identify homogeneity in the temporal trend of the fire regime. As the Euro-American Settlement of Boulder in the 1850s had a significant impact on the disturbance regime, this decade will divide the first two temporal groupings of homogenous fire regime. The Native American group will include dates prior to

1851, while the Settlement Period will include years 1851 until the policy of fire suppression was well underway in 1920 (Veblen et al. 1996). Although Settlement was only well underway by 1858, the year 1851 is used to demark the initiation of Euro-American influence and habitation in the Boulder area and to allow for comparison of the data with fire history reconstructions completed in the 1996 Veblen et al. study. The Native American period will also be separated into two groups in order to take into account the bias towards longer fire intervals resulting from the death of older trees and the resulting lack of older fire scars (Veblen et al. 1996). To allow for comparison of the Settlement and Suppression Periods, the Recent Native American Period is defined as 1781-1850, as in Veblen et al. (1996).

Groupings of plots based on spatial characteristics such as topographic position, aspect, and elevation, will be analyzed using the WMPI as well. As fire behavior and occurrence is thought to be influenced by these factors, the relative homogeneity of the fire regimes within and amongst these groups will be explored.

The WMPI, as an unbiased measure of central tendency, shows the exceedence probability, or the probability of fire intervals greater than a specified length of time. The WMPI is the fire interval associated with the exceedence probability of 50% (Veblen et al. 1996). Fire intervals for which 87.5 and 12.5 percent of the intervals fall above and below, respectively, are also presented along with the WMPI. Fire interval data are fitted to the WMPI distribution, and the goodness-of-fit is compared with that resulting from a normal distribution model using a one-sample Kolmogorov-Smirnov (K-S) test (Grissino-Mayer 1995). FHX2 also computes the reciprocal of the WMPI, the Weibull Fire Frequency Probability, which shows the likelihood of fire occurrence for any given year.

Fire reconstructions at each site were tested to determine whether the distributions of fire events better fit an empirical or Weibull distribution. If the empirical distribution was a better fit, the mean fire return interval would be used for the analysis. In most cases, excluding the analysis of entire data set as a whole, the Weibull distribution better described the data. This distribution was therefore used in the analysis of fire regimes for each site (e.g. Veblen et al. 1996).

Scar Occurrence, Fire Years, and Landscape Characteristics

Statistical tests were run to determine the significance of differences in fire regimes in relation to landscape characteristics. The mean fire return interval (MFI), the Weibull Distribution, and the variances of the groups were compared using two-tailed t-tests (both assuming and not assuming equal variances), the Kolmogorov-Smirnov test (K-S), and the F test, respectively (Grissino-Mayer 1995). These tests are standard for use in historical fire reconstruction analysis (Grissino-Mayer 1995, Veblen et al. 1996). Topographic, elevation, and aspect groups were defined at the plot level (1/10th acre) and grouped to provide adequate numbers of samples for statistical analysis. Group sizes were similar but not typically equal, at times requiring comparisons to be made for percentage of plots scarred and limiting fire reconstruction comparisons to a qualitative nature. Both scar occurrence across landscape features as well as historical fire regime metrics were analyzed.

Topography

Five topographic position groups were identified: ravine, lower slope, mid-slope, upper slope, and ridgetop. Each plot inventoried was categorized by the position of the center of the plot in relation to the surrounding landscape. Hilltops and knolls were categorized with ridgetops, as they are similar in abiotic features and are likely subjected to similar environmental influences. The number of samples in the ravine position (3) were too few to be used for the analysis.

Elevation

The elevation of each plot center was determined using GIS. Ranging from 5500-8000 feet, plots were divided into five groups; one for each 500 feet of elevation gain. Because each stand was sampled across the elevation gradient, stands are thoroughly divided amongst the groups, with each stand having plots in at least three groups.

Aspect

Aspects of each plot at plot center were determined using a compass and an estimate of the general azimuth of the entire plot. The fire history data from each plot was categorized into one of four aspect groupings: north (316-45 degrees), east (46-135 degrees), south (136-225 degrees), and west (226-315 degrees). Numbers of plots yielding datable fire samples with a southerly exposure were few (Table 3). For fire interval analysis, comparisons between aspects involving the southern exposure plots used a minimum of one sample scarred rather than the two-sample minimum otherwise adhered to. This enabled a statistical analysis of the differences between fire regimes involving the southern aspect. Comparisons between non-southern aspect fire history data maintained the use of a minimum number of two samples scarred for each fire event.

RESULTS

A total of 41 stands with 453 plots were searched for fire scarred materials, of which 27 stands and 115 plots yielded fire history information (25%). Stands ranged from 7 to 50 hectares, averaging about 11 ha in size. Of the 208 fire-scarred materials located, 167 were in extractable condition while the remaining materials were rotted or burned beyond recognition. Of the extracted samples, 130 wedges from individual trees cross-dated conclusively, yielding a total of 238 fire scars.

The majority of samples were taken from live ponderosa pine trees, with dead samples (remnant material, snags, downed woody debris) comprising 59 of the 72 live samples. Dates for each scar were established and analyzed (Grissino-Mayer 1995). For all interpretation of fire interval statistics, the median and the WMPI were significantly lower than the MFI. This reflects the skewedness of the fire interval distributions. A larger supply of data would likely bring the three measures of central tendency into concert (Veblen et al. 1996).

1. Landscape Characteristics and Occurrence of Scarred Materials—Plot Group Analysis

All plots with fire scarred material were inventoried for their elevation, aspect, species composition, and topographic position. Similar plots were grouped for the comparative analysis of descriptive fire interval statistics. For example, all the south-facing or Douglas-fir dominated plots in the montane zone were grouped together, regardless of where they occurred in the landscape. Groups ranged from 9 to 60 plots, while most included between 30 and 50 plots (Table 3). Using this systematic and dense sampling approach, these comparisons might lend insight into the patterning of fires in relation to landscape or vegetative features.

1. a. Species Composition and Elevation

Although more ponderosa pines yielded fire-scarred samples (110 out of 160), there is no correlation between the percent ponderosa pine composition in each stand and the presence of fire-scarred samples. While 81% of the samples taken from ponderosa pines was conclusively dated, only 68% of the Douglas-fir samples were in good enough condition to use in the analysis. Approximately 60% of the samples were from live trees. About 10% more ponderosa pine samples were extracted from live trees than were from Douglas-fir trees. The fire scars yielded from a single limber pine *(Pinus flexilis)* were the only representatives of other species of tree in this study.

In the montane zone of Boulder's public lands, the percentage of ponderosa pine generally decreases as elevation increases (Hogan 1993), while the relationship between elevation and number of scarred material found was positively linear, increasing with elevation up to 7500' (Table 3). Because the number of plots sampled in each elevation group was not equal, the percentage of plots yielding fire scarred material was determined. Plots at elevations between 5500-6000' and those between 7500-8000' had the highest percentage of scarred materials. Excluding the lowest elevation group, presence of scarred material generally increased with elevation.

1. b. Topographic Position

A majority of the scarred material was found in the middle of the slope of any sampled stand (48%), while the ravine plots yielded only one sample (Table 3). The upper slopes also supplied much of the fire history information (28%), as the ridgetops and the lower slopes followed in decreasing importance as locations for fire scarred material. Lightning scars were mostly found on ridgetops and middle slopes (23 scars in total), followed by the upper and lower slopes (10 scars total). The number of fire scars per topographic position was correlated with the number of lightning scars.

1. c. Aspect

West-facing plots yielded the highest occurrence of both fire- and lightning- scarred materials per plot sampled (44%; Table 3). North and east-facing slopes were second in percentage of plots supplying fire history information, while only 12% of the southern aspect plots encompassed fire-scarred material. Most lightning scars were found on northern and eastern aspects, while southern aspects had the least percentage of lightning scars.

2. Landscape Characteristics and Historical Fire Regimes

Upon comparing the fire regimes through history for topographic, aspect, and elevation groups (divided at the plot level, as above), significant differences were identified between all divisions using the student's t-test, the folded F-test for variance analysis, and the K-S test to interpret distribution patterns (see Methods section). In order to limit the influence of spot fires or error in identification of fire dates, analysis parameters included a minimum number of 1 trees scarred for each fire event and a minimum scarring of 10% of the group for each fire unless otherwise noted.

Because the groupings of the sampled plots has an inherent effect on the resulting fire history reconstructions, actual data should not be compared between the groups. For example, the mean fire return interval (MFI) for the middle slope of the topography group cannot be compared with the fire regime for plots in the 5500 to 6000' division within the elevation group. These two divisions of the elevation and topographic position groups may have overlapping samples. In addition, parameters for statistical data analysis may not be the same, as some divisions within the groupings did not supply adequate data for analysis using the above-mentioned > 10% scarred limitation.

2.a. Topographic Position

The fire regime analysis for the topographic positions was not able to take the ravine sample into account, as only one sample yielded a single fire scar and therefore no fire intervals.

Fire regimes in relation to topographic position were interpreted using the four divisions as above. Only fire events for which more than 10% of the division was scarred were counted. The mean fire return interval was shortest in the lower slope plots and longest for samples from the upper slope plots (8.2 and 14.4 years respectively; Table 3). Only two differences were found to be significant between the MFIs. The upper slope MFI was significantly different from that of the lower slope, while the upper slope MFI also differed from that of the ridgetop (Table 3). The number of fire intervals between the group's divisions was very similar, each group yielding between 14 and 19 fire intervals. As the most appropriate indicator of fire patterns, the Weibull Median Probability Interval (WMPI) showed a parallel ordination of fire probabilities to that of the MFI described above. Distributions were significantly different for each of the topographic group divisions (K-S test).

2. b. Aspect

Distributions of the fire event intervals were significantly different for each combination of aspect divisions (NE, NS, NW, ES, SW) except the eastern-western comparison. The WMPI was greatest for the southern aspect and lowest for the eastern aspect (Table 3). The fire return interval was longest for the south-facing plots, although this division was not found to have a significantly different MFI than the other divisions. With the shortest interval, the eastern aspect division MFI was significantly different from that of the northern aspect. The northern aspect was also statistically different from the MFI of the western plot (15.9 and 9.9 years respectively).

2. c. Elevation

Between 7501 and 8000', the mean fire return interval was significantly longer than for the four remaining elevation divisions (Table 3). The MFI increased linearly with elevation (r^2= 0.76), while the WMPI was also lowest for the 5500-6000' division but greatest for plots within the 6501-7000' in elevation. Significant differences between the first two elevations groups as well as