Tom Swetnam

FIRE HISTORIES OF UPPER ELEVATION FORESTS IN THE GILA WILDERNESS, NEW MEXICO VIA FIRE SCAR AND STAND AGE STRUCTURE ANALYSES

by

Rena Ann P. Abolt

A Thesis Submitted to the Faculty of the

SCHOOL OF RENEWABLE NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN RENEWABLE NATURAL RESOURCES

In the Graduate College

THE UNIVERSITY OF ARIZONA

1997

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of the requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under the rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgment the proposed use of the material is in the interest of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: ________________________

APPROVAL BY THESIS DIRECTORS

This thesis has been approved on the date shown below:

________________________ 3/31/97
Dr. Thomas W. Swetnam — Date
Associate Professor of Dendrochronology
and Watershed Management

________________________ 1 April 1997
Dr. Mitchel P. McClaran — Date
Associate Professor of Range Management

________________________ 18 APRIL 1997
Mr. Carleton B. Edminster — Date
Rocky Mountain Forest and Range Experiment Station
USDA Forest Service

ACKNOWLEDGEMENTS

This research was made possible by grants provided by The Gila National Forest and Rocky Mountain Forest and Range Experiment Station, U.S. Forest Service. I particularly wish to thank my committee members. Mr. Chris Baisan initially envisioned this project and all field work was developed under his guidance. I thank my major advisor, Dr. Tom Swetnam for hiring me as a Research Assistant and believing in my ability as a researcher and communicator. I thank Dr. Mitch McClaran for reminding me that I was in this adventure for myself, and for being a good friend. I thank Mr. Carl Edminster for supporting this project through the Rocky Mountain Station and serving as a committee member representing the real world (outside of academia). From all of my committee members I appreciate the suggestions and critiques during the data analysis and writing of this thesis.

I am especially grateful to Robert Abolt for his suggestions and critiques in the statistical analyses, organization, and presentation of the data. I could not have produced this thesis without his technical and emotional support.

Tricia Roller provided me with important suggestions on organizing my thesis exam presentation. I thank her for this and her friendship. I thank Mary Soltero for technical advice on the thesis format and support throughout my graduate career.

Particularly, I am also grateful to Margot Kaye for her support in map building of the study areas, as well as for her friendship. I wish to thank many others from the Laboratory of Tree-Ring Research for their comments and suggestions in the process of collecting, preparing and analyzing tree-ring data including Mark Kaib, Henri Grissino-Mayer, Matt Riser, James Riser, Matt Rollins, Robert Shay, Jorge Alazaga, Kiyomi Morino, and Jim Speer.

DEDICATION

This thesis is dedicated to:

- my husband, Robert Benjamin Abolt, a scientist who helped this humanist understand that science is a human discipline, and
- my family back in Georgia, who supported my academic quest, knowing only that it was important to me, and that was enough.

TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

LIST OF FIGURES

LIST OF FIGURES - continued

LIST OF TABLES

ABSTRACT

Fire-scar analysis to identify fire events and stand age structure analysis to identify fire effects on survivorship of trees were used to reconstruct surface and crown fire regimes in upper elevation forests of the Gila Wilderness, NM. Fire regimes varied across forest type, but not necessarily across elevation. Prior to the twentieth century, (from 1706 to 1904), the mean return interval for large fires was 8 years. During the twentieth century, (from 1904 to 1995), the mean fire return interval for large fires was 46 years. The virtual end of historically frequent fire regimes due to livestock grazing and fire suppression since the turn of the century has affected successional pathways of forest types across elevations, favoring later successional forest species and structures.

INTRODUCTION

Forest structure and species composition in the western United States are strongly influenced by fire (Peet 1988, Veblen 1992, Agee 1993, Johnson 1994). A marked decrease in fire extent since the turn of the century has resulted from livestock grazing effectively removing grasses which carried fires, and direct suppression of wildfires by government agencies (Leopold 1924, Dieterich 1983, Madany and West 1983, Savage and Swetnam 1990). From about 1904 to the present organized fire control activities were mounted and were increasingly effective in reducing the size of fires (Pyne 1982, Allen 1995). Decreased fire occurrence across Southwestern landscapes has favored vegetation change. Lack of fire has catalyzed shifts in composition towards later successional species, such as conversion of ponderosa pine forest to more shade tolerant mixed-conifer forest (Covington and Moore 1994, Spurr and Barnes 1980), replacement of aspen stands by mixed-conifer and spruce-fir (Jones et *al.* 1985) and invasion of montane grassland meadows by conifers (Allen 1989).

Rather than eliminating fire, organized fire suppression efforts combined with livestock grazing have dramatically altered fire regimes so trends in area burned per year and severity of burns are increasing since the 1900s (Swetnam 1990). The most often cited effects of fewer fires on forests has been increased fuel loads due to higher stand densities in the lower elevation ponderosa pine forest type. The absence of frequent fire allowed more small trees to survive, thus creating denser forests. Stands with higher tree densities are more susceptible to stand destroying wildfires. As a result, the open structures of pre-settlement ponderosa pine forests maintained by frequent, low intensity surface fires, have increasingly succumbed to intense, stand-initiating fires (Swetnam 1990, Covington and Moore 1994). The high severity and large size of these stand replacement burns are probably outside of the historical range of variability (*sensu* Morgan et *al.* 1994).

In contrast, stand-replacing fires were historically the norm in upper elevation spruce-fir and aspen forests prior to human alteration of fire regimes. Pre-white settlement fire regimes in spruce-fir forests of the Rocky Mountains were probably characterized by infrequent, intense stand-replacing crown fires (Jones 1974). Aspen clones have perpetuated for many thousands of years by the burning of high intensity crown fires which destroyed large areas of conifer forests allowing aspen recruitment into the stand openings (Jones and DeByle 1985). Although this general knowledge of spruce-fir/aspen dynamics is well established for the central Rocky Mountains (Spurr and Barnes 1980, Jones and DeByle 1985, Jones 1974), there has been virtually no research on these patterns in the Southern Rocky Mountains and the Mogollon Rim of Arizona and New Mexico.

Have frequency, size, and severity of fire in upper elevation forest ecosystems changed due to fire suppression? Forest inventories of montane and subalpine tree species in Arizona and New Mexico suggest this is the case. Forest patterns (stand age structure) have been altered by fire suppression. The area covered by conifer populations has increased, probably due to the reduced frequency of surface fires (Johnson 1995). Many of the central and southern Rocky Mountain aspen clones are being replaced by conifers and not regenerating due to fire exclusion (Jones and DeByle 1985). In the absence of crown fires, aspen populations have decreased by 46% in the Southwest, from 196,000 hectares (486,000 acres) in 1962 to 106,000 hectares (263,000 acres) in 1986 (Johnson 1995). Without the stand-replacing events critical to aspen recruitment, roughly half of the stands have experienced serious ingrowth of conifers during the last 25 years (Kaufmann et al 1994). Johnson (1995) warns that if this rate of decline of remnant, isolated aspen stands continues, aspen will cease to exist as a distinct cover type in about 25 years. To reverse the trend and avoid future loss of aspen groves--important for biodiversity, as well as aesthetics (USDA 1994), research on past fire regimes is needed to understand the role of high intensity fires in mixed-conifer and spruce-fir forests and to support the increasing role of prescribed fire in aspen restoration efforts.

Fire is often prescribed as a management tool to aid in the restoration of ecosystems altered by human-related disturbances such as fire suppression (Pyne et *al.* 1996, USDI and USDA 1995, Baker 1994, Agee 1993). In 1974, the Gila National Forest began one of the first prescribed natural fire (PNF) programs in the nation. Under this fire management policy, numerous lightning-ignited fires that met prescribed burning conditions were allowed to spread through grassland and ponderosa pine forests (Page and Garcia 1993). Prescribed burning in the upper elevation mixed-conifer, spruce-fir and aspen forests was avoided generally due to a lack of specific historical and ecological information on upper elevation fire regimes upon which appropriate wilderness fire management plans can be based. Regaining and perpetuating remnant aspen stands with stand-replacing burns requires innovative fire management beyond that currently in place in the PNF program (USDA 1994). The hesitation to prescribe intense fire behavior is understandable due to the inherent risk of high intensity fire. High intensity fires that typically burn into mixed-conifer and spruce-fir forests are less subject to control than low intensity surface fires that typically burn in lower elevation forest types. Improved knowledge and understanding of historical patterns (via forest composition, age and stand structure analysis) and processes (via fire-scar analysis) would provide a more sound basis for planning and implementing prescribed fires in these higher elevation forests. In particular, the relative role of surface and crown fires in mixed-conifer and spruce-fir forests is needed.

To predict ecosystem responses to future fire, an understanding of keystone processes (*sensu* Holling 1992) that operated in the past is required. By studying stand age structure and reconstructing historical fire regimes, we can address the role of past fires in creating and shaping the upper elevation forests of today, and by inference, what results various management strategies might produce. Fire-scarred trees are a direct, primary source of data on pre-settlement low intensity surface fire regimes, while stand age structure data (e.g. tree recruitment dates) can provide additional information on patterns of high intensity crown fire and subsequent tree recruitment. Direct evidence of fire in the form of fire scars is generally lacking in spruce-fir forests which sustain high intensity fires. To identify the occurrence of past fire, indirect evidence of fire's effects on age structure can be examined. Fire induces mortality and initiates subsequent recruitment in some tree species, thus creating apparent surges in recruitment. A fire-induced temporal pattern of recruitment would consist of a significantly higher survival rate of new recruits after a fire than survival of recruits before a fire. Initial cohorts establishing soon after a disturbance and subsequent cohorts usually have significantly different recruitment and mortality rates (Johnson and Fryer 1989).

Tree-ring analyses of fire history and stand age structure data can be used to characterize reference conditions of disturbance regimes in the past (Kauffman et al 1994). Most existing fire history studies describe how the frequency and character of the surface fire regime typical of lower elevation ponderosa pine forests has changed from pre-settlement times (Weaver 1951, Cooper 1960, Swetnam and Dieterich 1985, Allen 1989, Swetnam 1990, Covington and Moore 1994). Past fire history studies in Southwestern mixed-conifer forests show that in general, fire return intervals are longer in mixed-conifer forests than in pure ponderosa pine forests (Swetnam and Baisan 1996, Touchan et *al.* 1996). In some cases, however, fire frequencies in mixed-conifer were similar to those characterizing ponderosa pine (Grissino-Mayer et *al.* 1995), because fire frequencies are strongly dependent on landscape attributes such as slope, elevation and landscape connectivity as well as forest type (Swetnam and Baisan 1996, Swetnam and Baisan 1997). Because relatively few studies have been conducted in varying types of mixed-conifer associations and landscape configurations, conclusions on fire frequency cannot be generalized across all mixed-conifer ecosystems (Dieterich 1983).

Upper elevation coniferous forests of the Southwest are among the least studied ecosystems in North America (Peet 1988). They have been broadly described in terms of species dominance (Pase and Brown 1982, Peet 1981, Peet 1988), but published studies on structural organization in mixed-conifer and spruce-fir forests and historical disturbance regimes in the Southwest are virtually non-existent. The exception to this are two analyses of age and size-class distributions of living trees conducted in spruce-fir forests of the Pinaleno Mountains, New Mexico. Stromberg and Patten (1991) developed size/age regressions to estimate stand age from dominant trees, while Grissino-Mayer et *al.* (1994) dendrochronologically crossdated stumps of logged trees greater than 1 cm in diameter to obtain accurate tree ages to document age structure. The authors developed coarse reconstructions of century-scale fire frequencies in spruce-fir forests by dating ages of stands. It is likely that their use of traditional, static histograms of recruitment masked actual fire-related surges in recruitment. Comparable studies have not been carried out in upper elevation mixed-conifer forests.

Fire histories derived from fire scars provide direct estimates of past fire frequency and relative fire extent (Swetnam and Baisan 1996). Fire intensity or severity, however, can not be directly estimated from fire scars. Fire intensity is the degree of fire force as measured in flame length and energy per unit produced. Fire severity can be estimated by tree mortality, soil change, and fuel consumed. Scarring of trees by fire can be used to infer fire extent (Swetnam and Baisan 1996). In some circumstances, fire intensity/severity may be related to fire extent, but these relations are not well understood.

To estimate past fire severity, stand age structure must be analyzed to determine the impact of fire on forest structure. The relative impact of a fire on a stand can be measured based on the number of years where no evidence of tree survivorship exists prior to the fire event and subsequent surge in survivorship. Clumps of survivorship punctuated by preceding gaps in establishment dates suggests a disturbance setting (Johnson and Fryer 1989). Prior to this work, no study has examined effects of past fires and fire suppression on upper elevation mixed-conifer and spruce-fir forests in the Southwest using a combination of fire scars, age structure, forest composition and size structure data.

Hypotheses and Research Objectives

The goal of this study is to improve knowledge and understanding of historical and current fire regimes in upper elevation forests. By documenting the historical range of variability in fire regimes along forest type and elevational gradients, I tested the hypothesis that fire regimes varied according to forest type, elevation and forest management period. Fire-scar and stand structure analyses were used to meet the following research objectives:

1. Reconstruct historical surface fire regimes including mean fire return intervals, season of burning, and extent of burns along an elevational gradient from ponderosa pine through mixed-conifer to spruce-fir forests by examining fire scars and documentary records of fire.

2. Construct forest stand age structures in the mixed-conifer/spruce-fir transition zone to investigate stand history (determined from tree recruitment patterns) in relation to fire history (determined from fire scars).

3. Describe aspen stand origin dates in relation to surface fire history in adjacent conifer stands to identify occurrence of stand replacing fires.

4. Compare fire regimes and forest structure before and after the beginning of forest management (fire suppression and grazing) era to determine if processes (fire occurrence) and patterns (fire effects on forest structure) have changed in the twentieth century.

STUDY AREA

General Setting

The Gila Wilderness and adjacent primitive areas comprise one of the largest (306,844 ha) and oldest (established in 1919) areas under wilderness protection in the nation. The Gila Wilderness encompasses the headwaters of the Gila River and the mountains of the Mogollon Plateau in west-central New Mexico, 40 kilometers north of Silver City. The Mogollon mountains form a northwest-trending mountain mass approximately 65 km long and 25 km wide and rise to elevations of 3,312 m at Whitewater Baldy and 3,274 m at Mogollon Baldy Peak. From the crest of the mountains the land drops rapidly in all directions.

Geology and topography

The geologic structure of the Gila Wilderness was created by extensive volcanic activity at the close of the Cretaceous era when seas withdrew from the New Mexico region and regional uplift of the land, accompanied by mountain building began (USGS 1965). The earth's crust collapsed above a magma reservoir emptied by an explosive volcanic eruption to form a caldera. Renewed magmatic pressure elevated the subsided caldera to form a resurgent igneous dome within the caldera now called the Mogollon Mountains (Ratte et *al.* 1979). The western and southern faces of the mountains are the steepest and rockiest (Rixon 1905), while the east side descends with more gently sloping ridges that lead to mesa tops dissected by numerous stream cut canyons.

Sampling Areas

The study area extends from the summit down a ridge along the eastern face of the Mogollon Mountains (Fig. 1). The east slope is relatively mesic and thus supports prolific growth of subalpine tree species of the Petran Montane and Subalpine Conifer Forest life zones (Moir and Ludwig 1979), as well as montane grassland parks. This area was chosen for study because of its mosaic of different forest types, extent over an elevational gradient, and its inclusion of Langstroth Mesa (at the lower end) where a fire history in the ponderosa pine type was previously documented (Swetnam 1983, Swetnam and Dieterich 1985). Five managed fires have burned through Langstroth Mesa since 1978 (1984, 1989, 1992, 1996).

Human-induced disturbances in the region

Throughout the Holocene, humans have used the land and its resources to sustain themselves. Their use had variable effects upon the land that were both time and space specific. Our current knowledge of human land-use in the upper Gila watershed extends back at least to the Mogollon culture ca. AD 400 (Russell 1992). Later inhabitants were the Pueblo Indian cliff dwellers who lived in lower elevations south and east of the study area from circa AD 1270 to the early 1300s (Russell 1992). Their primary impact on the landscape was limited to the mesa tops and along the river where they hunted and

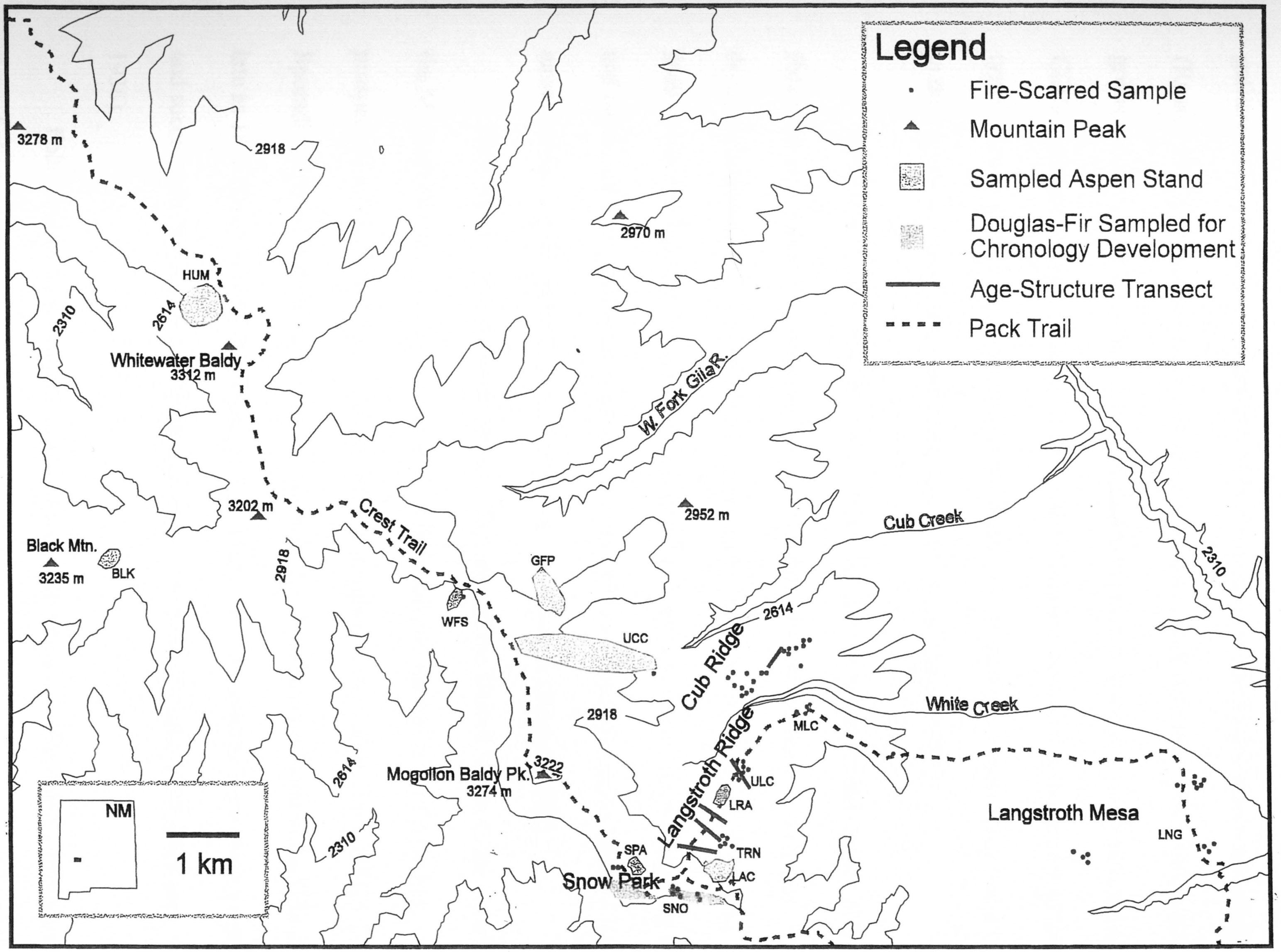


Figure 1. Map of study area including locations of stand age structure transects, chronology development core sites, aspen core sites, fire-scarred samples and sites.

gathered wild plants for food and maintained irrigation works to grow corn and beans (Russell 1992). Maize cultivation is universally associated with fire (Pyne 1982) and corn growers continue to burn their fields today. Open areas of grass and pines exist along the Gila's mountain streams (Murray 1988). Where humans occupied pyrogenic vegetation types, such as grassland and pine savanna, it seems reasonable to assume they had a hand in their ignition, maintenance and expansion (Myers and Peroni 1983).

Spaniards came to the Gila valley in the 1600s, where they mined copper at Santa Rita mine near Silver City and constructed irrigation ditches and shallow wells for domestic water supply (USDA 1965). In the early 1800s, nomadic bands of Apache Indians traveled through the area, never settling permanently in one place (Ferguson 1927) and cultivated corn and beans as needed (Murray 1988). They traveled to higher elevations during the summer to hunt white tail deer and elk (Russell 1992).

New Mexico was incorporated as a Territory of the United States at the close of the Mexican War in 1846, but, because of its isolation and the hostility of Apaches, prospectors and miners did not explore the new acquisition until after 1860 (USGS 1965). Sporadic outbreaks of violence between ranchers and Apaches continued in the Gila as late as 1885 (Bourke 1891, McKenna 1936). More Euro-Americans were able to settle and successfully ranch after Geronimo surrendered in 1885 (Bourke 1891, McKenna 1936).

Following numerous conflicts and battles with Spaniards, Mexicans and Americans through the late 1800s, the Apaches were removed by the US military (Russell 1992).

Apaches, Spaniards, Mexicans and Americans reportedly used fire in warfare (Kaib et al. 1996). In peaceful times, Apaches used fire for creating travel access, increasing visibility, driving game and trying to bring rain (Bourke 1891, Bahre 1985). Fires set purposefully or accidentally by Apaches may have occurred in the study area. However, abundant lightning in most areas of the Southwest, and particularly in the Gila Wilderness (Barrows 1978), indicates that human-set fires were probably not controlling past fire regimes, except in certain places and times (Swetnam and Baisan 1996, Swetnam and Baisan 1997).

The first settlers who tried to settle this country were either killed by Indians or run out by them. Later, after the Indian danger was over, a new bunch of settlers came. Unlike the prospectors before, they brought in small bunches of cattle and settled on small places. Henry Woodrow, the first Gila Wilderness Forest Fire Guard (1943).

Land use in the study area

Though accessibility to the area of study is usually limited during the winter and spring due to snow pack, the upper elevation forests have not been left unaffected in the past century by Euro-American settlers. Historical, human-induced disturbances on upper elevation forests in the Gila country included grazing by sheep and cattle, and fire suppression. Development of lower elevation lands by Euro-American settlers in the late 1800s may have affected adjacent upper elevation forests indirectly by altering the ability of fire to spread from lower elevation landscapes fragmented by cultivation, grazing and logging. Historical human-induced disturbances in lower elevations included mining, logging, agriculture, livestock grazing, and fire suppression.

Mining

Though mining began in the Silver City area in the 1600s, mineral development in the Gila Wilderness did not start until gold and silver were discovered in 1875 northwest of the wilderness in the Mogollon mining district (Ratte et al 1979). Gold-silver ore containing copper and lead was first shipped from the Mogollon district in 1879, and peak output was in 1913 (Giles 1970, Ratte et *al.* 1979). All but two mining camps, Finny and Cooney, closed down by 1905 (Rixon 1905). The cost of transportation at the time to move ore concentrates to the nearest shipping point in Silver City (90 miles away) consumed practically all the profits (Rixon 1905). With the discontinuation in 1893 of government purchase of silver, as once provided by the Sherman Act, a marked drop in the price ensued and the silver boom in New Mexico ended.

At its peak in 1913, the Finny mine in Mogollon supported a population of over 5,000 people. Aldo Leopold recruited fire fighters from Mogollon in 1922 to fight the Willow fire on Willow Mountain and wrote that the 1904 fire in Mogollon was fought by the miners gathered at Mogollon (Leopold 1922). The Finny mine continued operation until World War II.

Logging

The once heavily timbered areas around mining settlements were cleared of their pines to fuel silver, gold and copper mines, build and heat homes, and supply army troops at Ft. Webster (Silver City Press, August 2, 1974). Most of the timber removed was that growing along creek bottoms and along streams (Rixon 1905). Sawmills were located in canyon bottoms near wagon roads for lumber transport to mines. When the mines closed, the logging industry virtually ended, as it was unprofitable to transport lumber to the nearest railroad shipping point in Silver City. The designation of the land as the Gila Wilderness Area in 1924 removed it from further harvest. The forests within the Wilderness boundary have never been logged, though trees were felled within the study area to establish trails and to build a cabin and fire lookout tower on Mogollon Baldy (Woodrow 1943).

Agriculture

Agriculture was carried out to a limited extent only along the perennial streams that rarely run dry in lower elevations. A few farming settlements produced alfalfa and corn for the mining camps. But as mining camps closed, the farmer's market for products diminished. Rixon (1905) stated that no agriculture occurred in the upper elevations.

Livestock Grazing

Grazing of cattle and sheep was the most important industry in the region (Rixon 1905). Coupled with heavy logging in some areas, ground vegetation was denuded by overgrazing around canyon bottoms which led to flooding in the early 1890s and 1900s (Silver City Independent, May 31, 1904). In 1899, President McKinley decreed the area as the Gila River Forest Reserve, withdrew the lands from settlement to preserve them from further development, and called for no grazing on the forest preserve (Russell 1992, Silver City Press, August 2, 1974). Settlement did slow, but grazing did not. In 1903, Rixon (1905) cautioned that almost the entire Gila country was carrying too many cattle. In 1909, Gila Forest Ranger, Woodrow (1943), observed that there were cattle and sheep all through the mountains, and grass was hard to find. In the 1920s, overgrazing was recognized as a serious problem (Silver City Press, August 2, 1974). By 1928, numbers of livestock were reduced to 41,860 cattle and 52,269 sheep and goats (Silver City Press, January 4, 1938). In 1951, the New Mexico Department of Game and Fish purchased the Heart Bar Ranch and retired its grazing allotment through a cooperative agreement with the Gila National Forest (USDA 1951) in order to reintroduce elk without overgrazing the grasses within the wilderness (Russell 1992). With the passage of the Wilderness Act in 1964, livestock grazing was officially withdrawn throughout the Wilderness, other than that by transient pack outfits (Ratte et *al.* 1979).

Livestock grazing indirectly suppressed fire spread by removing grasses and herbs, that served as fuel to spread fire. Rixon (1905) examined forest conditions in the Wilderness in 1903 for the US Geological Survey and described a recently cut cattle trail that traverses the summit of the Mogollon Mountains, and sheep grazing along the summit that killed a young growth of pines in Snow Park. In 1912, three sheep camps were spread across the McKenna Park District from the mesa tops up to Mogollon Baldy. A total of 19,500 sheep were reported grazing the area (Woodrow 1943). Forest fire guard, Henry Woodrow (1943) complained that "there were cattle all through the mountains and grass [to feed his horses] was hard to find."

Fire suppression

At the turn of the century, fires were being fought in the Gila Wilderness. In 1900, M. Belden of Silver City was charged with the management of the Gila River Forest Reserve, which included fire fighting and preserving the Gila Cliff Dwellings from vandalism (Silver City Enterprise, July 13, 1900). Henry Woodrow was the first fire guard assigned to the Wilderness District in 1909 (Woodrow 1943). Fire suppression policy by the US Forest Service since 1905 mandated the complete suppression of all wildfires in the Gila country, until the establishment of the Prescribed Natural Fire Program in 1974. Though fires were ignited throughout the forest suppression period, effective fire control thwarted natural fire spread. Today some fires initiated by lightning that burn under prescribed conditions are allowed to continue burning as prescribed natural fires (PNFs) in the Gila Wilderness (Page and Garcia 1993). Lightning ignited fires that burn out of prescribed areas or conditions are deemed wildfires and suppressed.

METHODS

Because fire behavior and effects were probably more variable in upper elevation forests which sustained surface fires, crown fires, and subsequent aspen recruitment (Grissino-Mayer et *al.* 1994, Dieterich 1983, Ahlstrand 1980), a combination of methods were needed to reconstruct fire occurrence and impacts on forest structure. A review of written records of past fires and fire-scar analyses were employed to determine past frequency, seasonality, and extent of surface fires.

Aspen stand age analyses were used to determine past occurrence and extent of stand replacement fire. Because aspen is a principal successional species following stand opening fire events in these upper elevation forests, ancient burns are indicated by stands of quaking aspen (Rixon 1905, Jones and DeByle 1985). When the recruitment dates of many aspen trees are consistent and match fire-scar dates in adjacent conifer stands, these stand-initiating fires cannot be dated to the year. To determine if aspen stand origin dates may accurately be used as an indicator of the approximate year of disturbance (stand replacement fire), the establishment dates of codominant aspen trees were reconstructed in relation to the fire history developed from fire scars.

Age and size structure analyses were used to determine the effects of fire on stand history of mixed-conifer and spruce-fir forests. Stand age structure analyses involved measuring the sizes and arrangement of tree species, and aging living and dead trees to determine establishment and death dates, relationship between age and size, species composition, canopy levels and apparent recruitment surges and gaps over time (e.g., Parker and Parker 1994, Abrams et *al.* 1995).

Simple histograms present the demographic characteristics of populations. This age structure is constructed by counting the number of living trees at time *t* that were born in each time interval back into the past. With trees, age structures are generally static. The age structure taken at the time of sampling represents cumulative survivorship, not overall recruitment, because it lacks evidence of trees that did not survive (Johnson et *al.* 1994). Apparent surges in recruitment and recruitment gaps at individual sites that do not follow recruitment patterns across sites are assumed to be disturbance-induced rather than simply a function of regional climate. If recruitment is affected by disturbance, tree ages should by positively or negatively associated with disturbance dates (McClaran 1989).

Figure 2. Photograph of a fire-scarred ponderosa pine with fire history sample removed.

Modern Fire Records

Fire atlases compiled by the Forest Service (on file at Gila National Forest Supervisor's Office, Silver City, New Mexico) were studied for dates and locations of recorded fires that burned over 20 hectares (50 acres) since 1905. Historical documents written before 1950 were examined for mentions of fire events. These documents included the journals of Gila forest fire guards, Henry Woodrow (1943) and Aldo Leopold (1922), and articles from Silver City newspapers (starting in 1904).

Field sampling

Tree-ring chronology development

To produce a local tree-ring width chronology for crossdating samples, a climatically sensitive site (Fritts 1976) was located on a steep south-facing slope below Snow Park (Figure 1). Douglas-fir trees growing in an open stand were cored as near to ground level as possible with increment borers in an attempt to sample the root crown. Two cores were extracted from each of 56 trees. Relevant information about sampled trees (location, dbh, crown condition, lean degree and lean direction) were recorded on a standard specimen form.

Fire history from fire scars

To reconstruct historical surface fire regimes across forest types and elevations, forty-two fire-scarred trees were sampled at sites characterized as ponderosa pine, open mixed-conifer and interior mixed conifer (Tab. 1). Fire-scar collection sites ranged over a

700 m elevational gradient from Snow Park (3,080 m) to Langstroth Mesa (2,380 m). The sites included one in ponderosa pine (UCM-pine--Upper Cub Mesa samples 9-19), two in open mixed-conifer (SNP--Snow Park and UCM-mix--Upper Cub Mesa samples 1-8) and three in interior (closed) mixed conifer (MLC--Middle Langstroth Canyon, ULC--Upper Langstroth Canyon, TRN--Transect Ridge) (Fig. 1). Coupled with the fire-scar collection site in ponderosa pine at Langstroth Mesa (LNG) (Swetnam 1983), the area sampled spanned approximately ten kilometers in linear distance.

The fire-scarred trees chosen for sampling had the highest number of well preserved, healing ridges indicative of multiple fire scars (Fig. 2), which increased the probability of obtaining a more complete fire history record (Dieterich and Swetnam 1984, Swetnam and Baisan 1996). A crosscut saw was used to obtain full cross-sections from fire-scarred snags and logs, and partial sections from living trees (Fritts and Swetnam 1989). The sections were labeled and wrapped in strapping tape and/or plastic wrap to help prevent breakage and loss of pieces during transport to the laboratory. Drawings were made of each sample, and relevant information about each tree (species, dbh, crown condition, lean degree and direction) and microsite description (slope, aspect, ground cover, canopy cover) were recorded.

Fire history from aspen stands

To determine years when stand-initiating fires occurred, increment cores from 140 co-dominant trees were collected from nine aspen stands to date stand origin and estimate the timing and location of past "stand opening" fire events (Tab. 5). The nine aspen stands selected for dating were found at the heads of drainages and northeast flowing streams along the crest of the Mogollon mountains from Langstroth Canyon to Hummingbird Saddle, a distance of 16.5 km (Fig. 1). The stands were surrounded by Engelmann spruce/corkbark-fir forests. Six of these are monospecific aspen stands (HUM--Hummingbird Saddle, HBS--Hobo Springs, WFS—West Fork Saddle, UCC--Upper Cub Creek, SPA—Snow Park Aspen, LAC—Langstroth Canyon). Two of the stands are mixed with spruce and firs (GFP—Good Feeling Place, LRA—Langstroth Ridge Aspen).

The aspen stands were selected based on their large size and location on the crest, as well as their proximity to the stand structure transects. A minimum of four trees were cored in each stand at a height of approximately 0.2 m. Forty trees were sampled in one monospecific stand (UCC) to determine the range of age variability within stands. Fire-scarred conifers located within or adjacent to aspen stands were sampled in an attempt to document fire dates associated with stand initiation, wherever possible.

Table 1. Fire-scar collection site descriptions.

Site	Forest Type[1]	Elevation (m)	Aspect	Moisture	Location	No. of samples	Area[2] (ha)
SNP	MC	3,080	SE	intermediate	meadow transition	9	20
TRN	SF/MC	2,900	E	mesic	interior forest	4	3
ULC	MC	2,750	E	intermediate	interior forest	6	4
MLC	MC	2,700	NE	intermediate to dry	interior forest	4	13
UCM-mix	MC	2,650	E	dry	mesa transition	7	24
UCM-pine	PP	2,600	SE	dry	mesa	8	36
LNG	PP	2,380	E	dry	mesa	18	240

[1]MC = mixed-conifer; SF/MC = Spruce-fir/mixed-conifer; PP = ponderosa pine

[2]Fire scar sampled areas were estimated from a simple perimeter drawn around fire-scar sample locations.

Table 2. Aspen stand sites.

Site Name	Size of Stand[1] (ha)	Number of Trees Sampled
Langstroth Canyon (LAC)	6	9
Hummingbird Saddle (HUM)	103	12
Black Mountain (BLK)	60	13
West Fork Saddle (WFS)	17	4
Hobo Springs (HBS)	15	4
Upper Cub Creek (UCC)	29	40
Snow Park (SPA)	8	12
Good Feeling Place (GFP)	9	8
Langstroth Ridge (LRA)	4	11

[1]Aspen stand areas were estimated from the perimeter of the vegetation type from aerial photographs.

Fire history from mixed-conifer and spruce-fir stand age structure

To document stand history in relation to the fire history developed from fire scars, I subjectively established and examined stand age structure sampling transects to include the full range of canopy dominants present along the ridge crest. Five age structure transects (linear plots) were laid out in mixed-conifer and spruce-fir stands on the north facing ridges connecting the crest of the Mogollon Mountains to lower elevation ponderosa pine and Gambel oak (*Quercus gambelli*) dominated mesa tops below (Fig. 1). Three transects in spruce-fir stands (CRK, DFR, SPR) and one in mixed-conifer (ULC) were located on Langstroth Ridge above Langstroth Mesa, and one transect in mixed-conifer (CUB) was located on a ridge above Cub Mesa. Major species occurring in the mixed-conifer study sites were Douglas-fir (*Pseudotsuga menziesii* (Poir.) Britton), white fir (*Abies concolor* (Gorden and Gelendinning) Hoopes.), and quaking aspen (*Populus tremuloides* Michx.). Major species occurring in the spruce-fir study sites were corkbark fir (*A. lasiocarpa* (Hook.) Nutt. *var. arizonica* (Merriam) Lemmon), Engelmann spruce (*Picea englemannii* Parry), Douglas-fir, and quaking aspen.

Frequency and size of tree species in the mixed-conifer/spruce-fir transitional forest stands were measured to interpret stand structure. Increment cores were collected from living and dead trees to assess stand age, ages of cohorts, death dates, and to provide information on patterns of recruitment in relation to fire events.

Species, height, diameter, bark thickness, canopy position, and location along the transect were recorded from approximately 2,032 trees; 1,247 of which were seedlings (diameter typically <0.5 cm), 659 live adults and 126 dead adults. Seedlings were counted only. Species names of living and dead trees were identified in the field and cores were double-checked in the lab under the microscope for species-specific features (Kukachka 1960, Kellogg et *al.* 1982).

Each transect was divided into three nested belt transect plots (Fig. 3). All transects were at least 300 m in length, and some transects were extended in length in order to core at least 50 adult trees. Data were collected for all trees within 1 m along either side of the transect tape. From 1 to 2 m of the transect center, only individuals greater than 30 cm dbh were measured and cored, while from 2 to 3m individuals greater than 60 cm dbh were sampled. The sampling strategy was designed to increase the relative sample size of the larger size (oldest age) classes present in each stand, as these classes tend to occur at lower densities. Thus, wider belt transects increased the probability of sampling larger and potentially older trees needed to lengthen and improve the resolution of the temporal record of tree recruitment. Two increment cores were collected from each of 534 trees sampled from the lower bole at a coring height of approximately 0.2 (near root crown) meters, and 251 cross-sections were cut at root crown from living and dead saplings. When rot was encountered at the lower bole, increment cores were taken at 1.5 (breast height) meters. Cores were placed in paper straws and labeled.

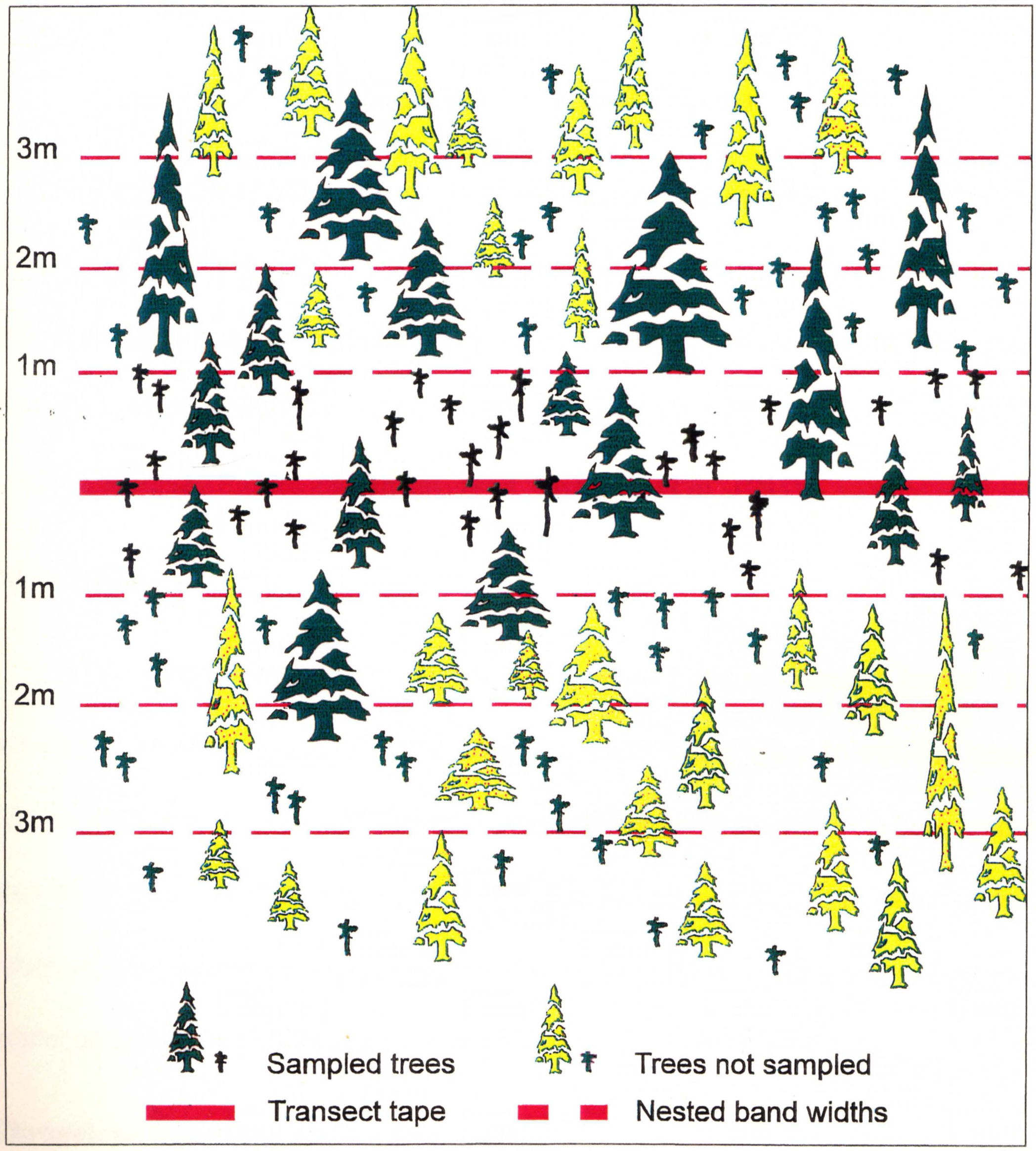


Figure 3. Schematic diagram of nested-width belt transect strategy for sampling stand age structure. Data was collected for all trees within 1 m along either side of the transect tape. From 1 to 2 m of the transect center individuals greater than 30 cm dbh were sampled. From 2 to 3 m trees greater than 60 cm dbh were sampled.

Locations of sampled fire-scarred trees, aspen stands, and stand age structure transects were mapped on 7.5 minute series topographic maps and recorded by a global positioning system device.

Dendrochronological analyses

Dendrochronology is the study of annual tree rings to reconstruct environmental history, such as the dating of tree establishment, death, injuries, and abiotic events they recorded (Fritts and Swetnam 1989). In order to assign each tree ring its exact year of formation, dendrochronological techniques for preparing and dating were used to date all sampled material (Stokes and Smiley 1968, Swetnam et *al.* 1985).

Preparation of samples

Fire-scarred sections were air dried, resectioned, and mounted (if necessary) in the laboratory. Increment cores were air dried, straightened and glued to wooden mounts. All samples were surfaced with an electric belt sander using successively finer sanding grits (from 40 to 400) to produce the high resolution surface needed to examine cellular structure and fire-scar positions within annual rings. All tree rings and fire scars were examined using a 30x binocular microscope.

Chronology Development and Crossdating

Crossdating was accomplished via the skeleton plotting technique (Douglas 1941, Stokes and Smiley 1965, Swetnam et *al.* 1985), and verified using the statistical crossdating program COFECHA (Holmes 1983) following measurement of annual rings.

Tree-ring width measurements were used to develop comparable tree-ring indices. Using the program ARSTAN, tree-ring widths were standardized using the negative exponential curve fitting option to remove the tree's biological growth trend and non-climatic low frequency variation (Fritts 1976). The resulting indices were averaged to produce the mean tree-ring chronology.

Fire-scar and increment-core samples were crossdated against the Douglas-fir master chronology from Snow Park. In some cases, the rings were too narrow to crossdate (e.g. suppressed saplings), so ages were estimated by ring counts.

Where the inner ring was near the pith, but the pith was not present, a "pith locator" was employed to estimate recruitment dates (Applequist 1958). Possible errors in estimating establishment dates included estimating pith dates with a pith locator, sampling at heights above root crown due to root rot, and counting rings where crossdating was impossible (e.g., tight rings due to suppression of growth via competition from a crowded forest) may have resulted in some error in approximating some tree establishment dates (Veblen 1992). I estimate that in most cases this error is within the range of plus or minus 5 years, based on the typical error in estimating the number of rings to pith sampled at ground level and error in using the pith locator method.

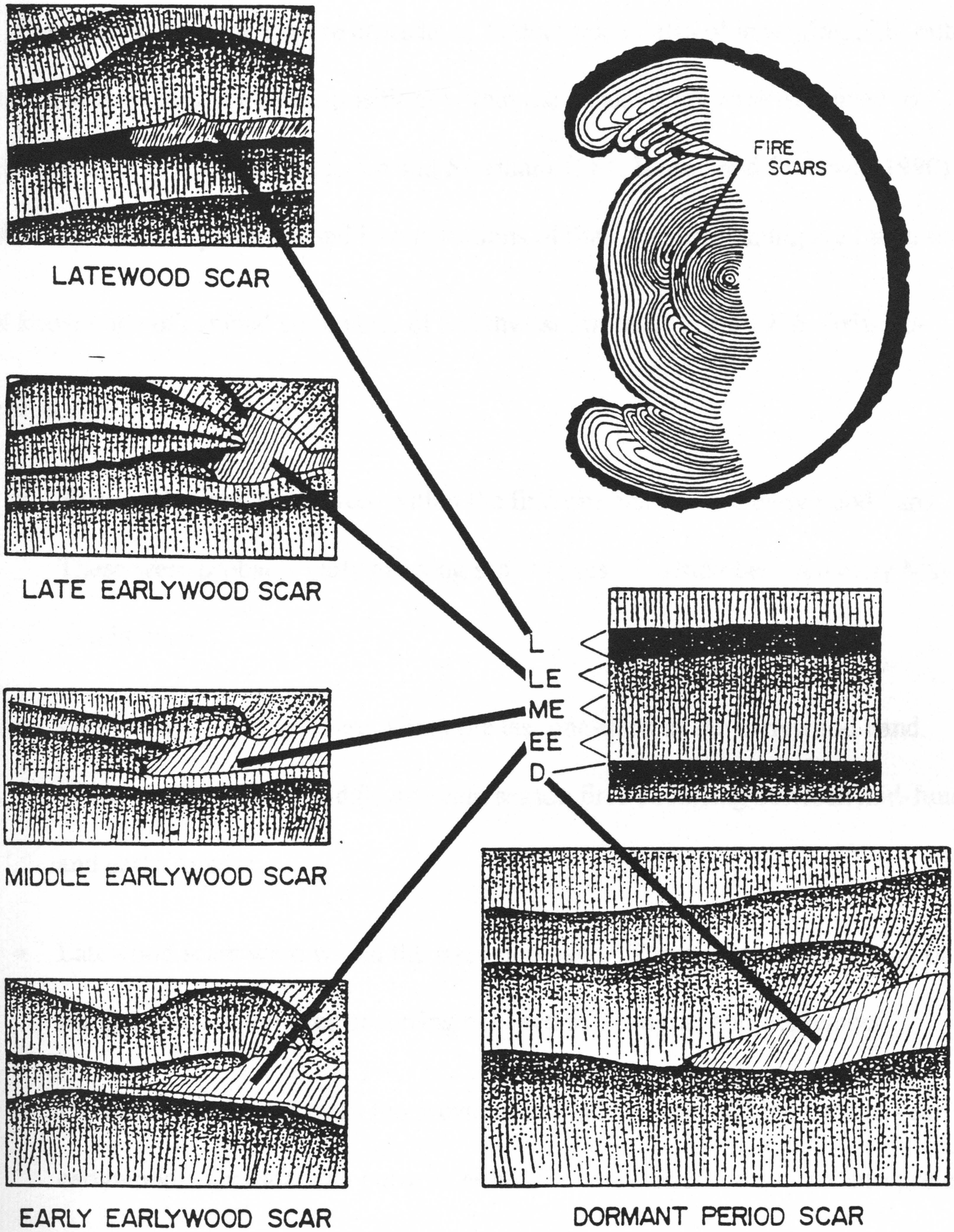


Figure 4. Schematic diagrams of fire-scar positioning. The position of a fire scar within the annual ring is used to estimate seasons in which fires occurred.

Timing of past surface fires

Fire-scarred specimens were crossdated to determine dates of inner ring/pith, outer ring/bark, and fire scars. Fire-scar positions within the annual rings were examined to estimate season of past burns (Dieterich and Swetnam 1984, Baisan and Swetnam 1990) The following fire-scar positions and interpretations of their seasonal timing are based on current knowledge of cambial phenology of Southwestern trees (Fritts 1976, Grissino-Mayer et *al.* 1994):

- Early-earlywood scars were within the first one-third of the earlywood band. These were probably early growing season fires occurring between early May to mid-June.
- Late-earlywood scars were within the last one-third of the earlywood band. These were probably middle growing season fires occurring between mid-June and early August.
- Latewood scars were within the latewood band. These were probably end of the growing season fires occurring between mid-August and September.
- Dormant scars lie between the previous year's latewood and the current year's earlywood. This scar can occur in either of two calendar years. As interpreted in the Southwest, dormant season fire scars represent events probably occurring prior to the beginning of spring growth.

Fire years and seasons were compiled for each sampled tree and entered into data files using software designed to analyze fire chronologies and fire return interval data from tree rings (Grissino-Mayer 1995). This program provides graphical output and computes descriptive statistics to facilitate analysis of historical fire regimes. The fire history analysis program was used to create fire chronology charts (Dieterich 1980), compare percentage of scars in different ring positions, and calculate mean fire return intervals. Two measures of central tendency of fire return intervals were computed: the mean and the Weibull median probability interval (WMPI). Since fire interval data are usually positively skewed, the simple mean is often a poor estimate of central tendency (Baker 1992). By modeling the fire return interval data with a Weibull distribution, more reliable estimates of central tendency are obtained (Johnson 1992, Grissino-Mayer et *al.* 1994). The WMPI estimates the fire interval at which there is a 50% probability of shorter or longer fire intervals occurring (Grissino-Mayer et *al.* 1994, Swetnam and Baisan 1996).

Extent of past fires

Patterns of synchrony and asynchrony of fire dates among trees and sites can be used to infer the relative extent of fire events across various spatial scales (Swetnam and Baisan 1996). If specimens recording the same fire date were scarred by the same fire, agreement of fire-scar dates between specimens and sites not separated by topographic barriers to fire can indicate relative fire extent within a site and across sites. Even if different fire events (i.e., non-continuous burns) caused the synchronous fire-scar dates, these fires can be reasonably inferred to represent relatively more extensive burning than fires recorded by few trees or only one site (Swetnam and Baisan 1996).

Fires that scarred at least 20% of the specimens were considered to be fire years of relatively large extent. The 20% cutoff emphasizes more extensive or widespread fire years, while de-emphasizing fire years that were probably smaller, scarring only a few trees (Swetnam 1990, Grissino-Mayer et *al.* 1994, Swetnam and Baisan 1996).

For fires that were only recorded at one site (20% cutoff), the minimum extent of the area burned was estimated as the size of the entire site. To estimate the minimum spread of fires within individual collection sites, we took the perimeter of the actual sample points and estimated the area within the perimeter. The actual area burned is much larger than the site area, since fires could easily have spread into sites from distant locations.

Extensive fire years were considered fire events recorded by at least 20% of the specimens within at least three sites across the entire elevational gradient sampled. As a coarse estimate of the possible shape and minimum extent of past large fires, I first examined the shape of twentieth century (1909-1995) fires in the Wilderness mapped by the Forest Service. Since all of these fires were more-or-less contained by suppression or confined by prescription (i.e., PNFs), they were certainly minimum size. The suppression effects (e.g., fire lines) and changes in fuel loads and types in the twentieth century probably introduced biases in the size and shape distribution of these fires. Overall, however, the bias is probably toward much smaller fire sizes in the twentieth century than in earlier centuries, because they were suppressed. Thus, it is reasonable that these data provide a quantitative basis for estimating minimum fire areas represented by fire-scar data.

All burns had at least one similarity in their shape; they were longer one way than the other. The amoebae-like form of the burns can be approximated by an oval or elliptical shape, with a minor and major axis. I measured the width and length of 75 mapped burns to produce an average width to length proportion of the minor relative to the major axes. The distance between the furthest recorded sites is assumed to be the major axis or length of the burn. The result was a computed proportion of 0.48 (i.e., the minor axis is approximated as 0.48 times the maximum distance). The minimum extent of the fire was approximated by determining the elliptical area from the average ratio and major axis. The equation for deriving these estimated minimum areas were as follows:

Area of an ellipse

$$\pi * (major/2) * (minor/2)$$

From the ratio

$$minor = 0.48\ major$$

Substitution yields

$$area = (0.48\pi/4) * major^2$$

In this application of the principle of uniformity (i.e., the present is key to the past), I assumed that the shape of post settlement burns was proportionally the same as presettlement burns. Given limitations to this assumption—in particular, that present conditions (e.g., fuel loads) were not the same as past conditions, such that shapes of past burns may have been more complex, this method was obviously not an absolute measure of fire size. However, it provides a reasonable basis for standardizing and estimating minimum area of past burns based on fire scars for comparative purposes. The minimum extent of past fires probably did not stop at our sampled points (trees sampled) on the landscape. Though possible, it was unlikely that estimated fire sizes were smaller than actual fire sizes. Although it was possible that some synchronous fire dates were due to separate, non-continuos burns, synchronous fire dates among sets of the sites most probably reflected fires that burned within and between sites because no major fire barriers existed between sampled sites. Overall, the method was probably quite conservative in quantifying relative minimum areas of burns. For example, area of burn determined by the ellipse method for Langstroth Mesa was one-fifth of the actual area burned during a prescribed fire in 1992. The value of this measure, therefore was primarily in comparison of relative values.

Aspen stand origins

Inner ring/pith dates were recorded from co-dominant aspen trees to estimate dates of stand origin. Aspen stand origin dates were compared with fire dates derived from fire scars to identify years of past surface fires with stand-initiating components. Aspen stand areas were estimated from color aerial photographs (1:15,000, October 1992). The areas of aspen stands were considered to be the minimum sizes of stand-replacement burn patches, since the original perimeters of aspen stands indicative of such burns have been partially obscured or replaced by conifers.

Stand age structures of mixed-conifer and spruce-fir stands

From the mixed-conifer/spruce-fir stand age-structure transects, inner ring/pith, outer ring/bark, fire scar, and other injury year dates were recorded. Estimated tree establishment dates, sizes, species and positions along the transect were entered into spreadsheet files to analyze temporal and spatial patterns of surviving recruits, species composition and density, forest structure and correlation between size and age within stands.

<u>Size-age relationships</u>

Because recruitment dates of many trees were not possible to determine due to heart rot, we analyzed species specific age-size relationships in hopes of estimating tree age from size measurements. An attempt was made to predict age from size measurements with enough precision to identify post disturbance recruitment rate change in stand structure. To find a regression model that gives the best correlation and smallest standard deviation, least squares regression equations and correlation coefficients were calculated using age as the independent variable and diameter at breast height (DBH), basal area (Πr^2), and basal area*height as dependent variables.

Survivorship rate differences

Fire affects tree recruitment and mortality. Young trees without fire-resistant bark recruited prior to a fire tend to be destroyed by even a mild surface fire. Because fires destroy most young trees, the period immediately prior to a fire is expected to generally lack evidence of surviving recruits (hereafter referred to as "survivorship"). Clumps of survivorship punctuated by preceding gaps in establishment dates suggests a disturbance setting (Johnson and Fryer 1989). It is expected that the survivorship after a fire would be significantly higher than the survivorship of trees that recruited before a fire. To quantitatively indicate changes in rate of survivorship a method of differences was used.

Surges in survivorship into the forest stand were examined to identify disturbance events such as fire. Histograms of tree establishment dates in age classes of 2-year, 5-year and 20-year increments were created from actual tree age data for each species in each transect.

Most fire histories involving stand age structure analysis identify fire dates as the year preceding apparent surges in tree survivorship depicted in histograms with non-overlapping time increments, which I refer to as "stationary histograms". Because the beginning point of the time increments or window is arbitrary, the stationary histogram window may mask or hide survivorship events because the time period before and after the fire year do not coincide with the placement of the histogram period. In previous studies, these surges have not been quantified numerically, only represented graphically in stationary histograms. To quantify survivorship surges, difference in survivorship numbers before and after each year were calculated. Changes in survivorship rate between 10-year periods before and after individual years were examined across a 2-year moving (running) histogram.

The differences between survivorship in successive 10-year periods were plotted on 2-year increments from 1700 to 1972. Survivorship pulses were defined by year of relative maximum difference in survivorship prior to and following that year and involved a difference of 3 or more trees. Peak survivorship years are years with significantly less survivorship for some period (e.g. 10 years) prior to a given year than a period of equal length (e.g. 10 years) after the given year, indicating a post-fire setting. Disturbance events (e.g. fire) and impacts at a site were inferred by identifying maximum change in survivorship rate before and after individual years.

To compare severity of one fire event to another, a survivorship rate difference number was calculated as the number of trees recruiting in the period after a date divided by the sum of trees recruiting before and after the date. To obtain a number indicative of relative survivorship difference, survivorship rates were standardized by dividing by the sum of the survivorship for both periods and multiplying the relative difference by the actual difference (number of trees). An equation for survivorship rate difference number (SRD) follows:

SRD =

$$\frac{S_{t2} - S_{t1} * |S_{t2} - S_{t1}|}{S_{t1} + S_{t2}}$$

where S_{t1} = survivorship in preceding 10-year period

S_{t2} = survivorship in subsequent 10-year period

The ratio of post survivorship rate to the sum of survivorship before and after (SRD) indicates a measure of survivorship rate change at a site varying positively and negatively to infinity. For example, if post survivorship is 5 and prior survivorship is 0, [(5-0)/(5+0)*5] = 5. If survivorship continued at a steady pace, the same numbers recruited could be expected before and after the year examined, such that the SRD would be 0 if post survivorship is 5, and prior survivorship is 5, [(5-5)/(5+5)*0]= 0.

<u>Stand structure measurements</u>

Percent dominance of species and stand composition were measured in several ways. Basal area per hectare was computed from DBH measurements to examine the structural importance of individual size classes (0.5-30 cm, 30-60 cm and >60 cm DBH) within and between stands. Difference in plot sizes for different tree sizes were standardized as stem numbers (density) per hectare. Basal area and number of trees per hectare of each species were computed, as well as the percentages of each species within transects based on these measures. Importance values were then calculated as the average of the two percentage values (density and basal area) for each species in each transect.

Dominance and co-dominance among the species is shown by height and DBH of trees mapped at different locations along the transect. Maps of sampled tree ages and positions along the transect allowed me to determine if survivorship events were localized to a portion of the transect or spread over the entire transect. Localized areas of survivorship events indicate the impact of disturbance (e.g., fire events), while continuous survivorship along the transect indicates absence of disturbance.

RESULTS

Historical records of fire occurrence, 1900 to present

Large fires (> 20 ha) recorded in the study sites by Gila National Forest personnel during the twentieth century were 1909, 1953, 1978, and 1992. Forest Service records show that many other large fires occurred near the study area (1920, 1938, 1943, 1946, 1950, 1952, 1953, 1956, 1965, 1968, 1974, 1978, 1984, 1989, 1990, 1992), but were not allowed to spread to study sites due to effective fire suppression. Prescribed Natural Fires in 1978, 1984, 1989 and 1992 were confined to burn primarily on Langstroth Mesa. It is also likely that some other smaller fires (e.g., single tree, lightning-ignited burns) also occurred within the study area, and were suppressed, but I do not have access to records of these fires.

Additional fires documented in historical records occurred within the study sites in 1904 (Silver City Independent May 31 and June 28, 1904, Leopold 1922), 1909 (Woodrow 1943), and 1918 (Woodrow 1943). The 1904 fire year was documented in The Silver City Independent newspaper on May 31, 1904 as "a forest fire which is destroying much valuable timber…raging in the Mogollon mountains to the east side of Baldy, and in the vicinity of Mogollon and Rain Creeks. On June 28, 1904 the newspaper reported that "[many] forest fires in the Mogollon mountains which for a time were partially extinguished by showers, were last week reported as having broken out again". Aldo Leopold (1922), who was inspecting the forest at the time for the Forest Service, wrote in his diary on June 2, 1922: "Warner suggests that big fires in certain localities may require certain fixed numbers of men to control. Suggests looking up the 1904 fire." The 1922 Whitewater fire created extensive aspen stands north of the study area.

Tree-ring chronology

A tree-ring chronology was developed from Douglas-fir trees in Snow Park to assist in crossdating fire scar, cross section and increment core samples (Fig. 5). Narrow tree rings indicate dry years, while wider rings are the result of more favorable growing conditions (Fritts 1976).

Fire history recorded from fire-scars

Fire occurrence

A total of fifty-seven fire-scarred sections were crossdated to produce a record of fire occurrence extending over four centuries (Fig. 6). Fire scars recorded this century confirmed fire years documented in written accounts, and contributed two more fires to the record occurring in 1906 and 1964).

The fire-scar record shows that the period before forest management was characterized by a much higher fire frequency than the period after circa 1904. These fires were frequent and widespread across sites (Fig. 7). A sharp decrease in fire occurrence characterizes the twentieth century fire suppression era. Only 7 fires were documented after 1904 (91 years), compared to 67 fires between 1567-1904 (337 years).

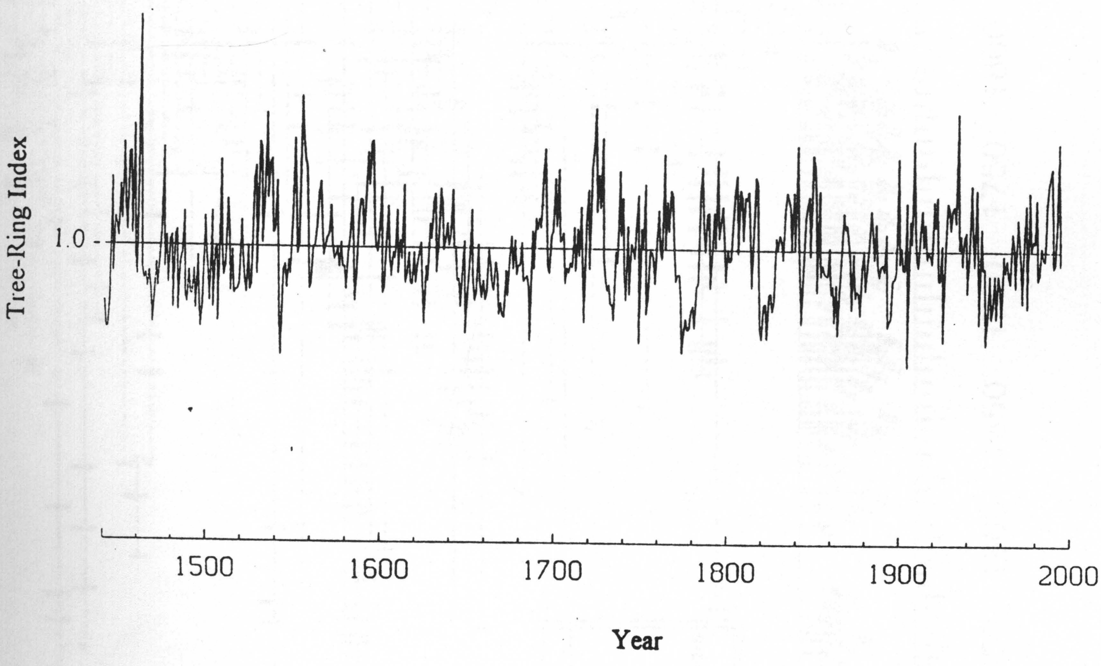


Figure 5. Snow Park Douglas-fir tree-ring width chronology. Tree-ring indices falling lower than the mean represent relatively narrow rings, while indices rising high above the mean represent wider rings and more favorable growing conditions.

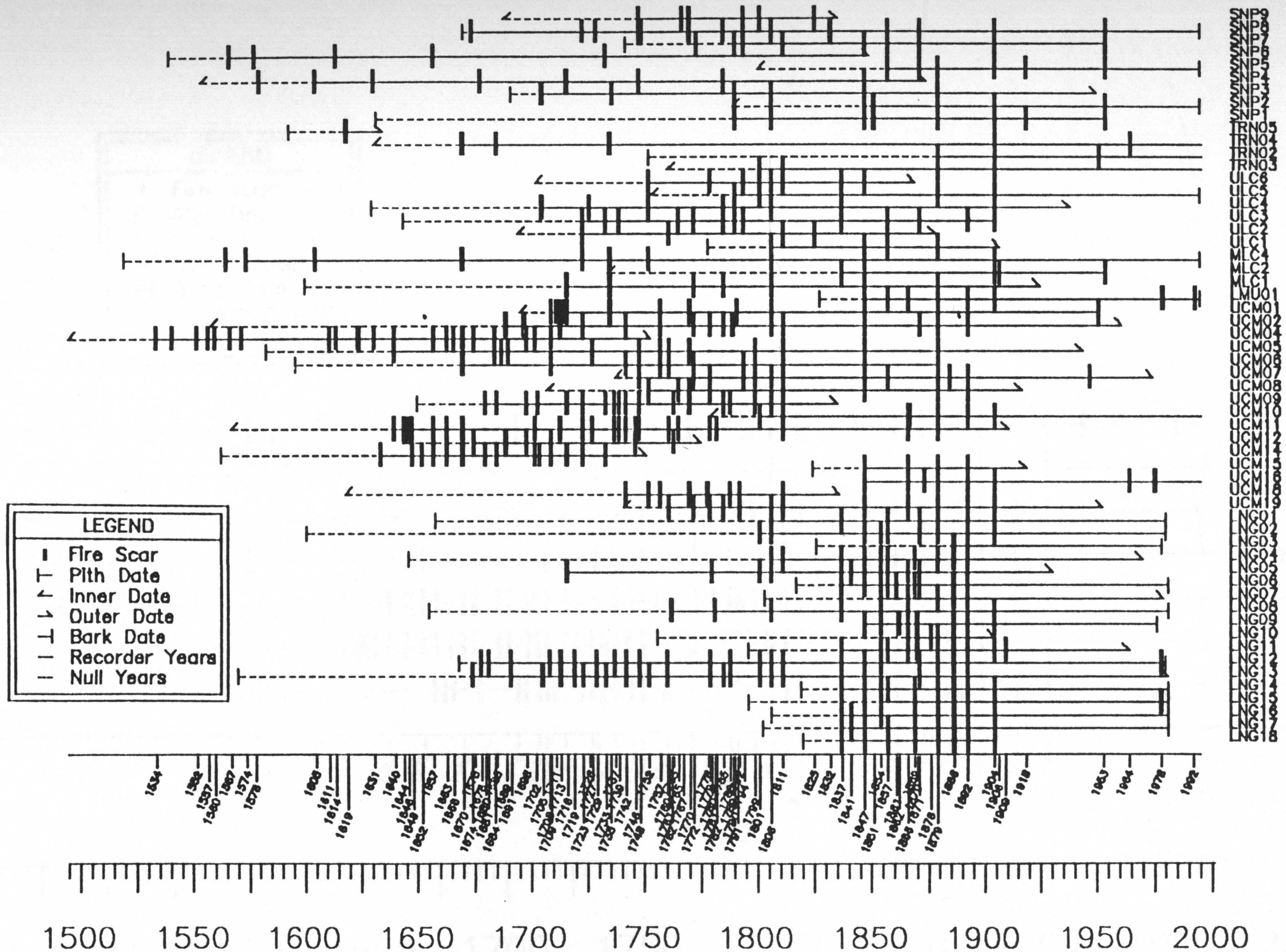


Figure 6. Master fire chronology chart from fire scars. Fire-scarred tree sample identifications are listed on the right according to location from highest elevation site at Snow Park (SNP) to lowest elevation site at Langstroth Mesa (LNG).

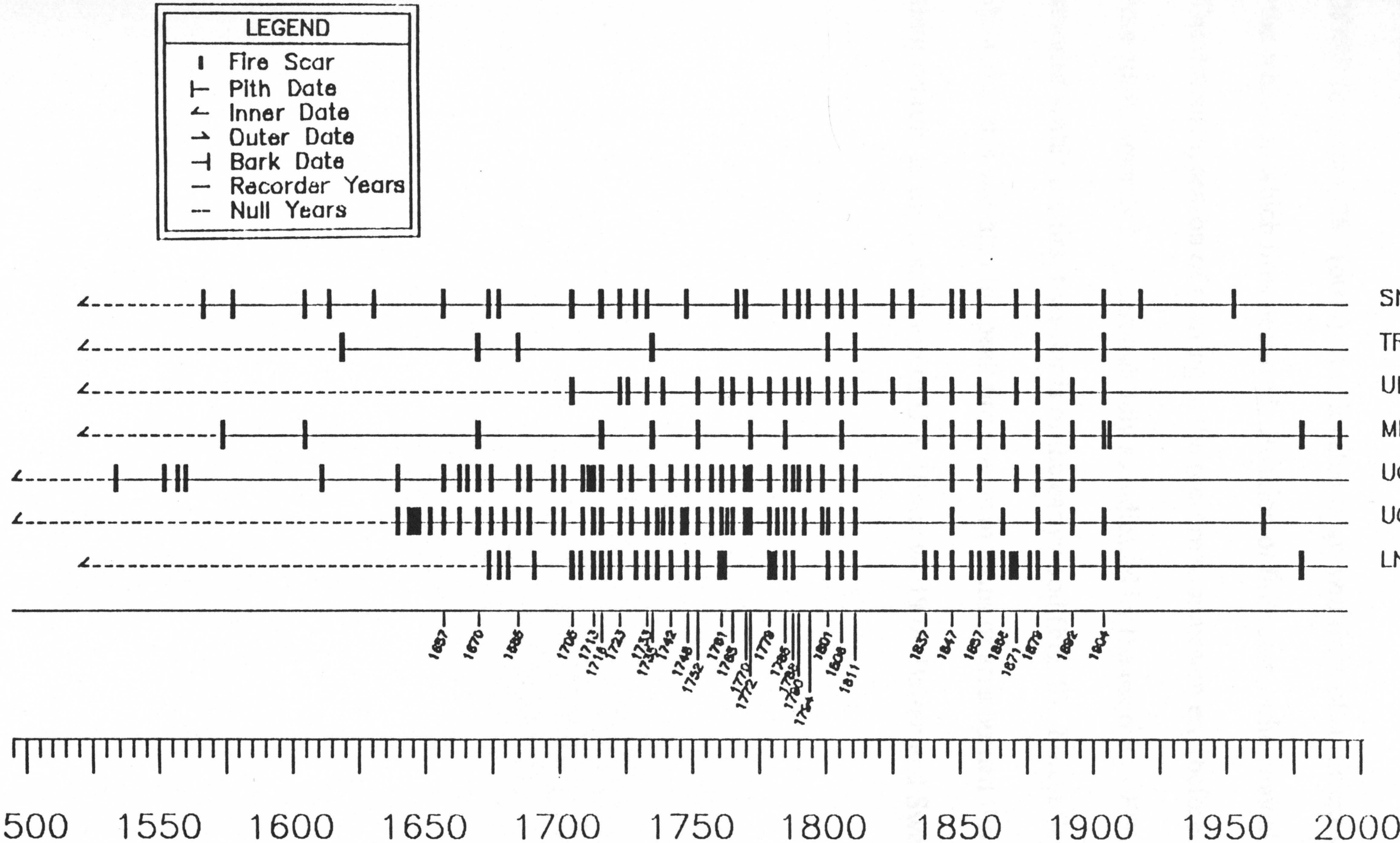
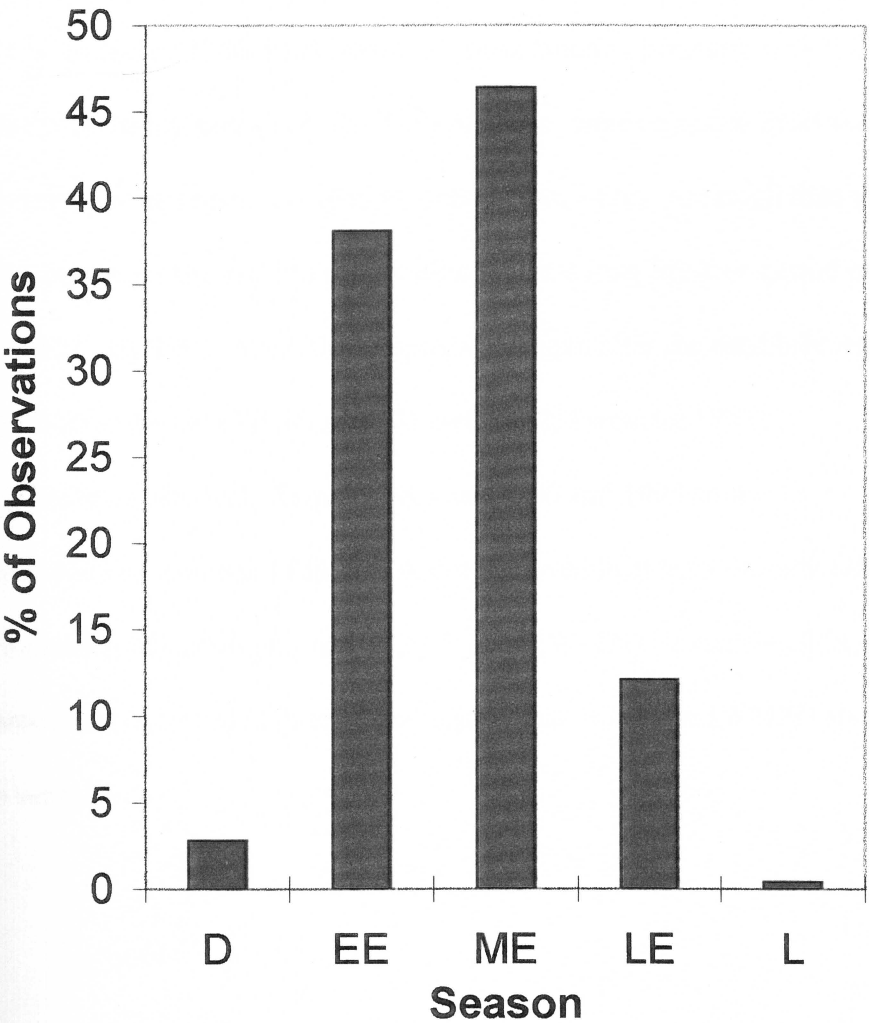


Figure 7. Composite chronologies from fire-scar collection sites. Extensive fire years recorded across at least three sites are noted. These fires were recorded by 20% or more of the sampled trees within each site. Sites are listed on the right in order of elevation. SNP= Snow Park, TRN= Transect, ULC= Upper Langstroth Canyon, MLC= Middle Langstroth Canyon, UCM= Upper Cub Mesa, LNG= Langstroth Mesa.

Season of burning

Of 480 fire scars, 281 (60%) were located in growth rings of sufficient width to estimate the season in which fires occurred. Position of fire scars within annual rings varied. The dominant season of scarring in the pre-fire suppression era (before 1905) ranged from approximately May through July as indicated by the majority (99%) of fire scars positioned within the first two-thirds of the earlywood (Fig. 8). Forest Service records show that this was also the peak fire season in terms of area burned throughout the twentieth century in the Southwestern U.S. (Barrows 1978, Baisan and Swetnam 1990).

Figure 8. Season of burning from the period 1534 to 1995. Seasonal distribution of fire scars from 43 trees sampled across the elevational gradient. Fire scar positions are listed as D= dormant, EE= early earlywood, ME= middle earlywood, LE= late earlywood, L= latewood.



Fire Return Intervals

Forest Service records show that twentieth century fires (1904 to present) occurred at some point along the east slope of the Mogollon Mountains on average about once every 3 years. Almost all of these fires were suppressed, and so did not spread into the study sites to scar sampled trees. Since 1904, the median fire return interval was 13 years (WMPI) (Tab. 3). However, it is evident that twentieth century fires were overall much less frequent and extensive than in earlier centuries (Figs. 6 & 7).

The period of 1706-1904 was used for computing pre-suppression fire return intervals for the study sites (Tab. 3). By 1706, fires were recorded in all sites and at least one extensive fire had been recorded at three or more sites. Although fires were generally frequent throughout the pre-fire suppression era, one long fire-free period occurred from 1811 to 1837. By 1905, direct fire suppression began after the establishment of the USFS jurisdiction over the Gila Wilderness (Russell 1992, Swetnam 1983).

Fires were relatively frequent between 1706 and 1904 across the range of elevations sampled (Tab. 3). A fire occurred in at least one site sampled along the elevational gradient about once every 3 years (WMPI). Extensive fires (recorded in at least three sites) occurred at intervals of approximately 8 years (WMPI) and ranged from 2 to 26 years.

Table 3a. Pre-fire suppression period fire return intervals in years, 1706-1904.

Site[1]	Type[2]	WMPI[3]	Mean	Min.	Max.
SNP	MC	10	12	3	41
TRN	SF/MC	37	42	10	68
ULC	MC	8	8	3	14
MLC	MC	15	15	9	31
UCM	MC	9	7	2	36
LCM	PP	5	6	2	36
LNG	PP	5	6	1	26

[1]SNP= Snow Park, TRN= Transect, ULC= Upper Langstroth Canyon, MLC= Middle Langstroth Canyon, UCM= Upper Cub Mesa, LCM= Lower Cub Mesa, LNG= Langstroth Mesa
[2]MC= mixed-conifer, SF/MC= spruce-fir/mixed-conifer transition, PP= ponderosa pine
[3]WMPI= Weibull Median Probability Interval

Table 3b. Pre-fire suppression period fire return intervals across the elevational gradient in years, 1706-1904.

Period	% Scarred[1]	WMPI[2]	Mean	Min.	Max.
1706-1904	All fires (≥ 1%)	3	3	1	14
1706-1904	Large fires (≥ 20%)	8	9	2	26
1904-1996	All fires (≥ 1%)	13	14	1	20
1904-1996	Large fires (≥ 20%)	46	46	43	49

[1]% Scarred= percent of samples scarred across sites
[2]WMPI= Weibull Median Probability Interval

Fire frequency did not clearly decrease with elevation (Fig. 9). Regardless of elevation, fire frequencies did not vary substantially among the more open mixed-conifer stands [SNP, ULC, MLC] along the ridge. Mean fire return intervals for large surface fires (scarring least 20% of the trees sampled in individual sites), however, decreased as a function of forest type. Longer fire return intervals characterized the relatively mesic spruce-fir and mixed-conifer stands, while shorter fire return intervals characterized drier pine stands (Fig. 10). Surface fires occurred least frequently in the mesic mixed-conifer/spruce-fir transition stand (TRN).

No fire scars were found in the spruce-fir forest type, although basal scars created by bears were common. The average fire return intervals measured from fire scars (as WMPIs) were 5 years in ponderosa pine, 11 years for mixed conifer, and 37 years in mixed-conifer/spruce-fir transition forests.

Fire extent

It is reasonable to infer that synchronous fire years across different sites located on a landscape not divided by topographical fire barriers represent relatively widespread fires compared with asynchronous fire years. Maps of twentieth century fires show that some fires spread across elevational gradients, uninhibited by topography. It is very likely, therefore, that pre-settlement fires spread between lower and upper elevation forests (Figs. 6 and 7).

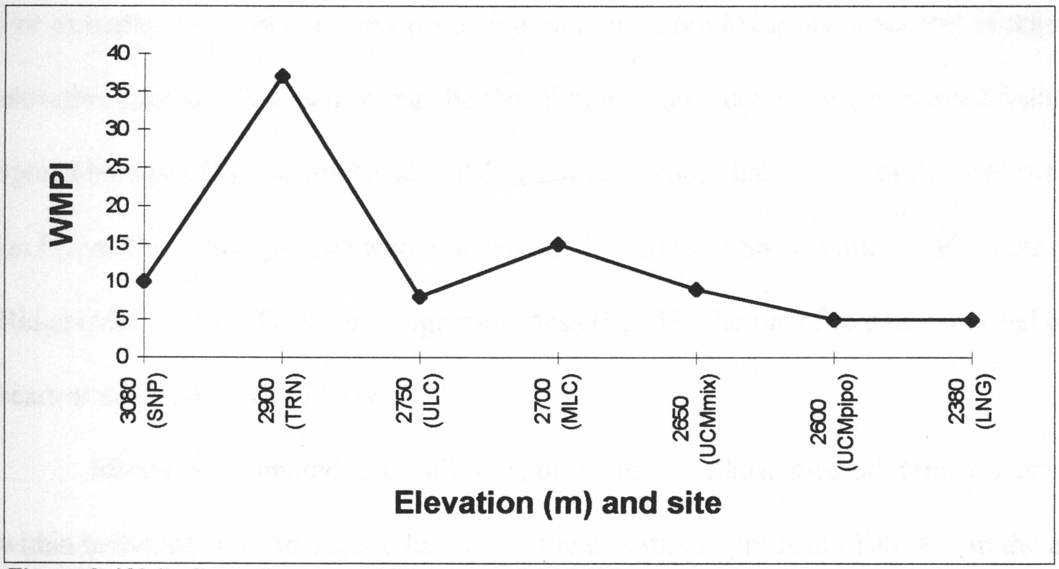


Figure 9. Weibull median probability interval (WMPI) across elevations and sites. SNP= Snow Park, TRN= Transect, ULC= Upper Langstroth Canyon, MLC= Middle Langstroth Canyon, UCMmix= Upper Cub Mesa, UCMpipo= Lower Cub Mesa, LNG= Langstroth Mesa.

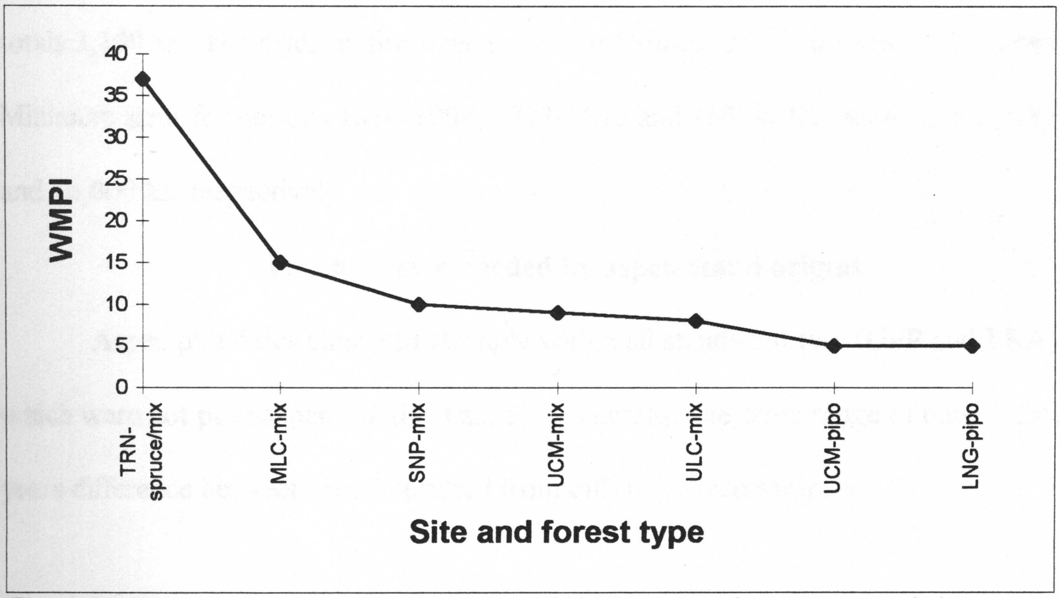


Figure 10. Weibull median probability interval (WMPI) across forest types and sites. SNP= Snow Park, TRN= Transect, ULC= Upper Langstroth Canyon, MLC= Middle Langstroth Canyon, UCMmix= Upper Cub Mesa, UCMpipo= Lower Cub Mesa, LNG= Langstroth Mesa.

For example, 18 of 26 fire dates occurring on Langstroth Mesa also occurred in upper elevation forests. However, it may be that White Creek occasionally interfered with fire spread between Langstroth Ridge and Cub Mesa, because half (51%) of the fires recorded on Upper Cub Mesa (UCM) were not recorded by trees in Snow Park (SNP), Langstroth Ridge (MLC, ULC, TRN) or Langstroth Mesa (LNG). The only fire date recorded by fire scars at every site was 1879 (Fig. 7).

Minimum estimated sizes of burns, based on the ellipse method, ranged from 6 ha within individual sites to 10,260 ha across the elevational gradient (Tab. 4). In the area studied, fires tended to be larger during the period prior to fire suppression than today. Minimum sizes of fires affecting the study area since forest management (1905-1995) totals 3,100 ha. Historically, fire sizes were 5 to 7 times greater than during this century. Minimum sizes for periods 1814-1904, 1723-1813 and 1632-1722 were 22,560, 18,670 and 16,000 ha, respectively.

Fire history recorded by aspen stand origins

Aspen pith dates clustered strongly within all stands but two (GFP and LRA) which were not pure aspen stands (Tab. 5). Generally, the same range of dates (about five years difference between trees) resulted from different-sized samples.

Table 4. Estimated minimum extent of fires (1534-1994) based on elliptical fire sizes of a width:length proportion of 0.48. The length axis was estimated from synchronous fire dates among sites.

Minimum extent	Collection sites[1]	No. fires	Fire years (additional sites affected)
10,260 ha	HUM <=> LNG	1	1904
3,050 ha	GFP <=> LNG	1	1748
2,800 ha	SNP <=> LNG	18	1674 (UCM), 1678, 1705 (ULC), 1716 (MLC, UCM), 1723 (ULC, MLC, UCM), 1729, 1733 (ULC, UCM), 1785 (ULC, MLC), 1801 (TRN, ULC, MLC), 1806 (ULC, MLC, UCM), 1811 (TRN, ULC, UCM), 1847 (ULC, MLC, UCM), 1857 (ULC, MLC, UCM), 1871 (ULC, UCM), 1879 (ALL)
2,000 ha	UCM <=> LNG	9	1713, 1737, 1742, 1752 (MLC, ULC), 1779 (ULC), 1788, 1866 (MLC), 1892 (MLC, ULC), 1964 (TRN)
1,900 ha	DFR <=> LNG	1	1837 (MLC)
700 ha	SNP <=> UCM	2	1657, 1794 (ULC)
600 ha	SNP <=> MLC	1	1605, 1953
300 ha	TRN <=> UCM	2	1685, 1735 (MLC)
260 ha	TRN <=> MLC	1	1670
240 ha	LNG	8	1723, 1780, 1841, 1854, 1869, 1886, 1978, 1992
200 ha	SNP <=> ULC	2	1790, 1825
170 ha	ULC <=> UCM	1	1739
60 ha	UCM	22	1534, 1552, 1557, 1560, 1640, 1644, 1646, 1648, 1652, 1663, 1698, 1702, 1709, 1719, 1727, 1746, 1782, 1784, 1788, 1790, 1799
20 ha	SNP	7	1567, 1578, 1614, 1631, 1832, 1851, 1918
13 ha	MLC	2	1574, 1906
6 ha	ULC	1	1726
3 ha	TRN	1	1619

[1]HUM= Hummingbird Saddle, LNG= Langstroth Mesa, GFP= Good Feeling Place, SNP= Snow Park, UCM= Upper and Lower Cub Mesa, DFR= DFR Transect, MLC= Middle Langstroth Mesa, TRN= Transect The site collection sites shown with "⇔" between them indicate the two most distant sites recording the fire date, and these sites were the basis for the long axis of the ellipse.

Stand-initiating fire years

Aspen stand origins were coincident with fire-scar dates sampled from conifers in 1748, 1904 and 1953 (Tab. 5). The aspen stand at GFP established after a fire in 1748. To my knowledge this is the oldest known aspen stand yet reported in the literature. Spruce and corkbark fir have become dominant over most of this stand since their establishment in the 1830s.

Stands originating in 1904 were BLK, UCC, WFS, HBS, LAC, and HUM. Remnant conifers found on the perimeter of the stands recorded the aspen stand initiating event with fire scars in 1904. A few older Douglas-fir trees (1560s-1730s) were scattered throughout the stands and recorded injuries from a fire in 1879, as well. The 1953 Lookout Canyon fire recorded throughout Snow Park initiated the aspen stand below the park. This fire is documented in Gila National Forest fire atlases.

Aspen stand sizes

Aspen stand sizes ranged from 6 ha to 103 ha (Tab. 2). These areas probably represent a minimum extent of patches of high intensity crown fires in the study area. Establishment of conifers along the perimeter since the fires has probably decreased the original size of stands.

Table 5. Aspen stand establishment dates.

Site name	Probable Fire Origin Date	Range of Pith Dates
Langstroth Canyon (LAC)	1904	1904-1909
Hummingbird Saddle (HUM)	1904	1904-1907
Black Mountain (BLK)	1904	1904-1918
West Fork Saddle (WFS)	1904	1904-1906
Hobo Springs (HBS)	1904	1904-1908
Upper Cub Creek (UCC)	1904	1904-1909
Snow Park (SPA)	1953	1953-1954
Good Feeling Place (GFP)	1748	1748-1762
Langstroth Ridge (LRA)	multiple	1760-1812

Stand age structure history of mixed-conifer and spruce-fir forests

Size-age relationships

The relationship between diameter and age is described by curvilinear regression equations using basal area as the independent variable (Figs. 11a-11e). The percent variance of tree age explained by tree diameter was highly variable according to site and species (Tab. 6). Highest R-squared values ($p > 0.05$) for each species were 0.89 for aspen, 0.82 for Douglas-fir, 0.78 for white fir, 0.74 for spruce, and 0.65 for corkbark fir.

Although these relationships are strong, the ability to predict age from size with a high temporal resolution (i.e., 1 to 5 years) is weak. Comparative histograms of survivorship from DFR produced from predicted and actual ages show that true age structure of these forests cannot be represented by size-age regressions (Figs. 12a-12b). High standard deviations and broad 95% confidence limits suggest that age or age structure can not be accurately estimated from diameter of upper elevation tree species with enough resolution to identify dates of establishment. For regression analysis to provide useful information on survivorship surges, the standard deviation must be smaller than the expected fire return interval. In mixed-conifer forests the expected fire interval is much less than 20 years.

Table 6. Coefficients of determination (r^2) and standard deviation between basal area and age for tree species in all age classes. All coefficients are significant ($p < 0.05$).

SPECIES[1]	TRANSECT	r^2	σ (years)	NO. TREES
PIEN	ALL	0.74	14.9	48
	SPR	0.35	10.9	20
	CRK	0.8	26.2	10
	DFR	0.27	10.6	16
ABLA	ALL	0.21	30.2	98
	DFR	0.09	27	42
	SPR	0.65	19.3	31
	CRK	0.55	29.5	25
ABCO	ALL	0.67	26.5	130
	SPR	0.78	20.4	11
	CRK	0.55	26.9	10
	DFR	0.43	12.3	3
	ULC	0.74	30.3	52
	CUB	0.26	16.4	54
PSME	ALL	0.62	46.3	172
	ULC	0.62	46.2	13
	DFR	0.6	50.5	39
	CUB	0.67	13.5	56
	SPR	0.55	52	34
	CRK	0.64	43.7	32
POTR	ALL	0.57	37.9	62
	ULC	0.03	14.2	8
	SPR	0.89	21.1	13
	DFR	0.48	48.3	21
	CUB	0.37	17.3	11
	CRK	0.56	46.4	9

[1]PIEN= spruce, ABLA= corkbark fir, ABCO= white fir, PSME= Douglas-fir, POTR= aspen

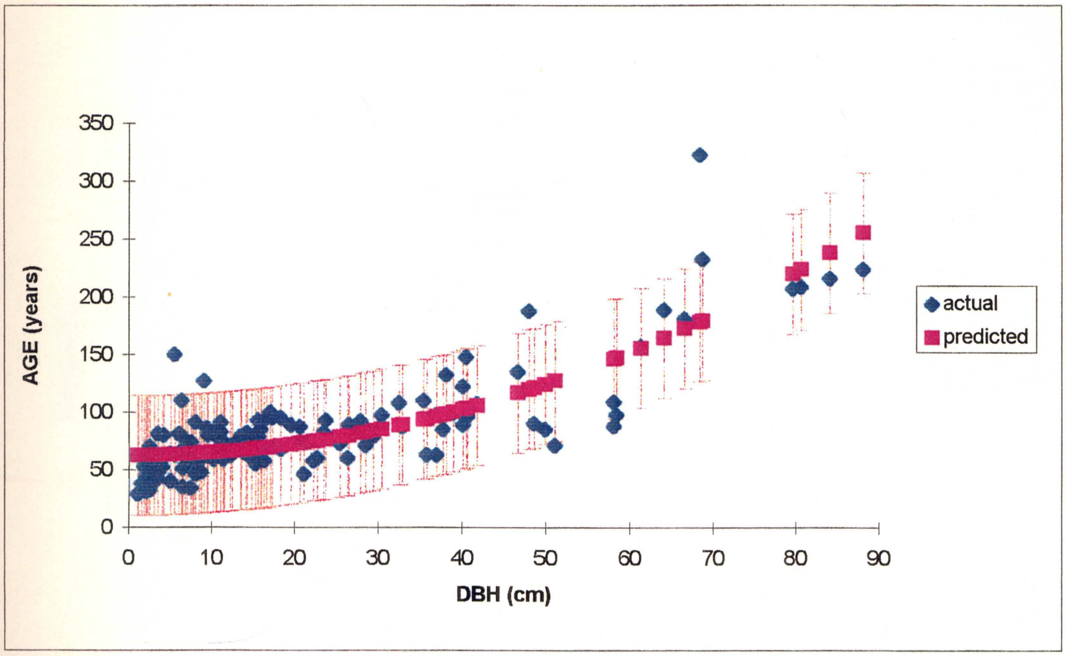


Figure 11a. White fir scatter plot of age vs. basal area. Red-dotted bars represent 95% confidence limits.

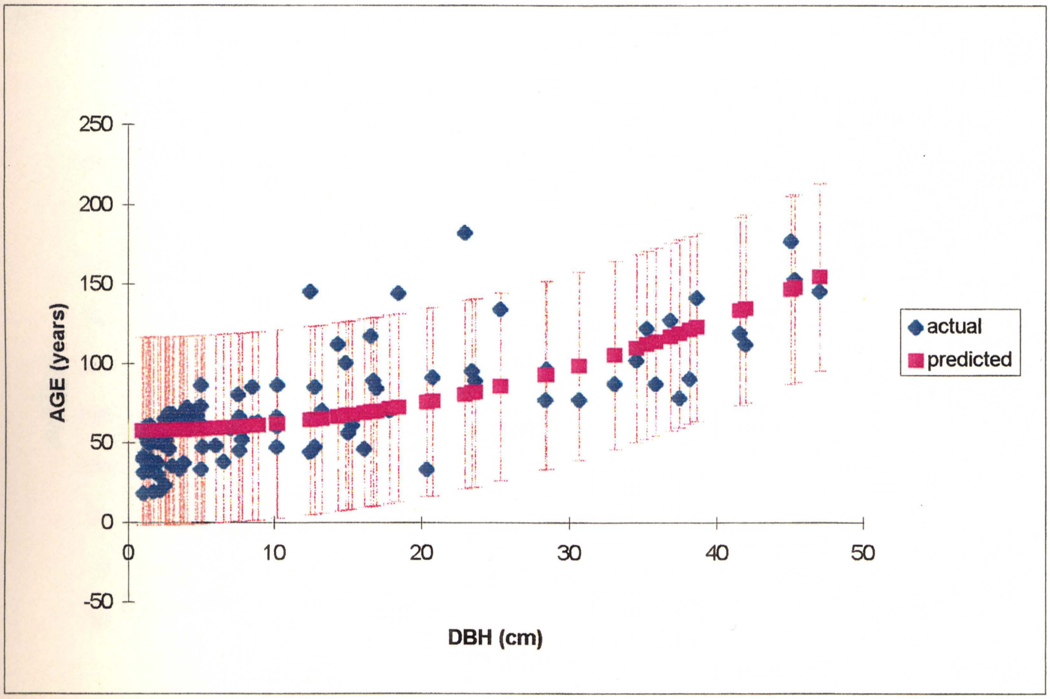


Figure 11b. Corkbark fir scatter plot of age vs. basal area. Red-dotted bars represent 95% confidence limits.

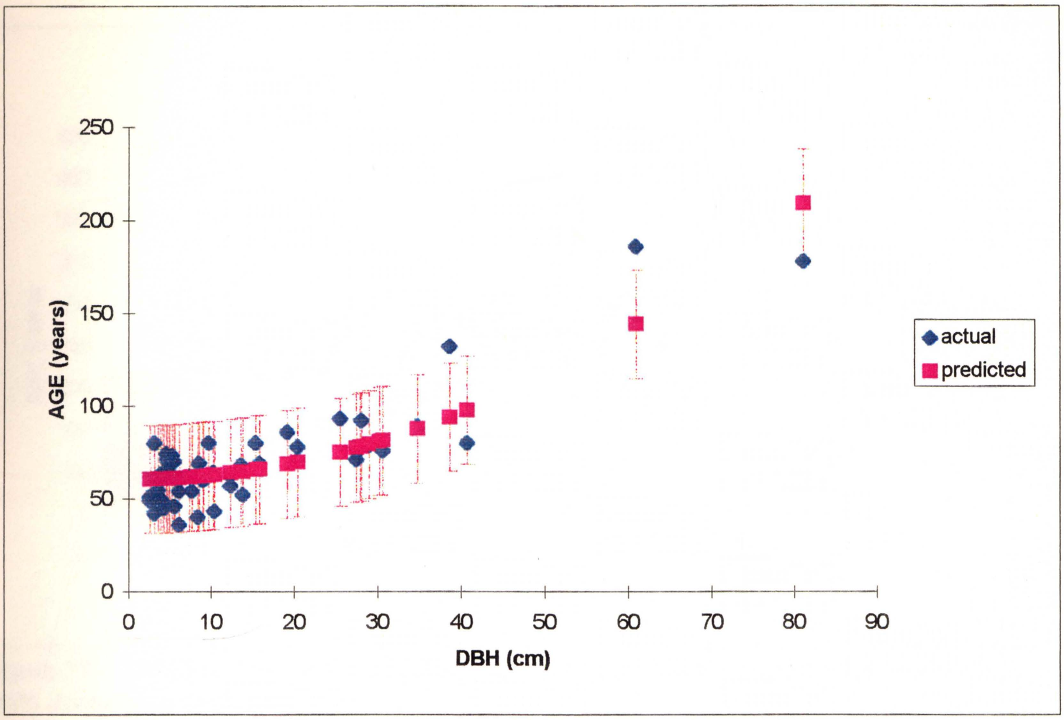


Figure 11c. Engelmann spruce scatter plot of age vs.basal area. Red-dotted bars represent 95% confidence limits.

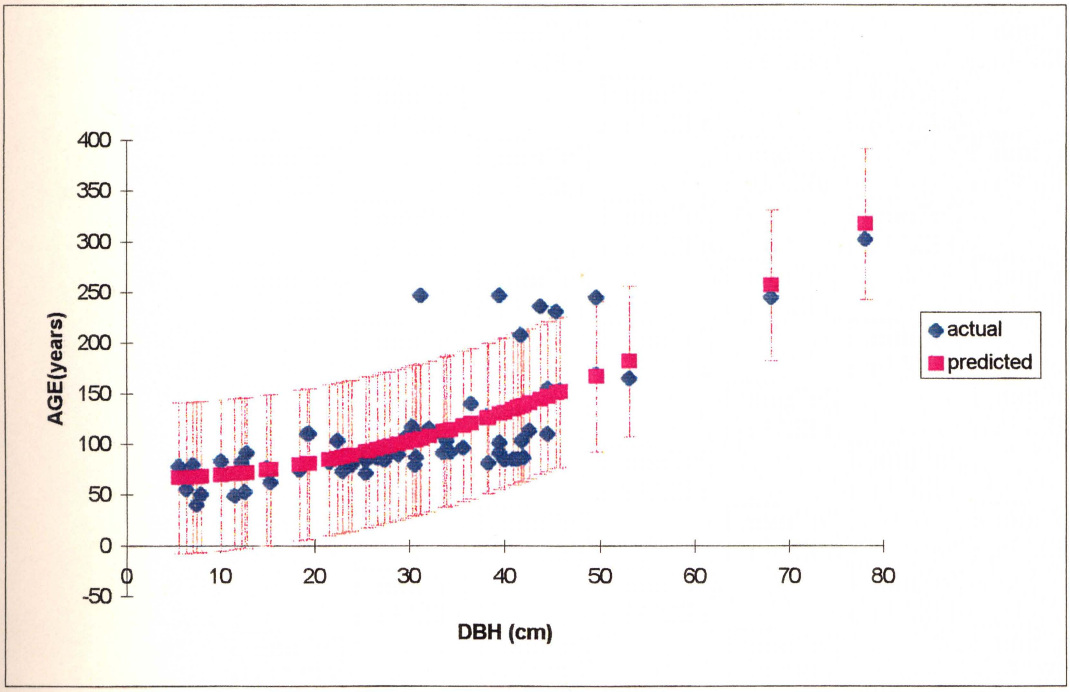


Figure 11d. Aspen scatter plot of age vs. basal area. Red-dotted bars represent 95% confidence limits.

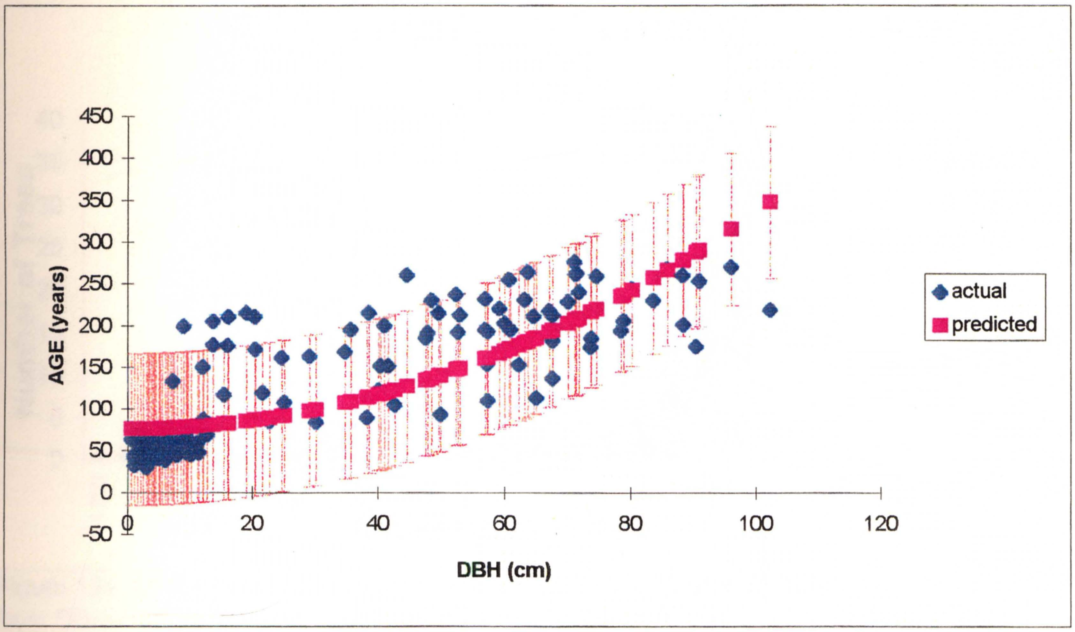


Figure 11e. Douglas-fir scatter plot of age vs. basal area. Red-dotted bars represent 95% confidence limits.

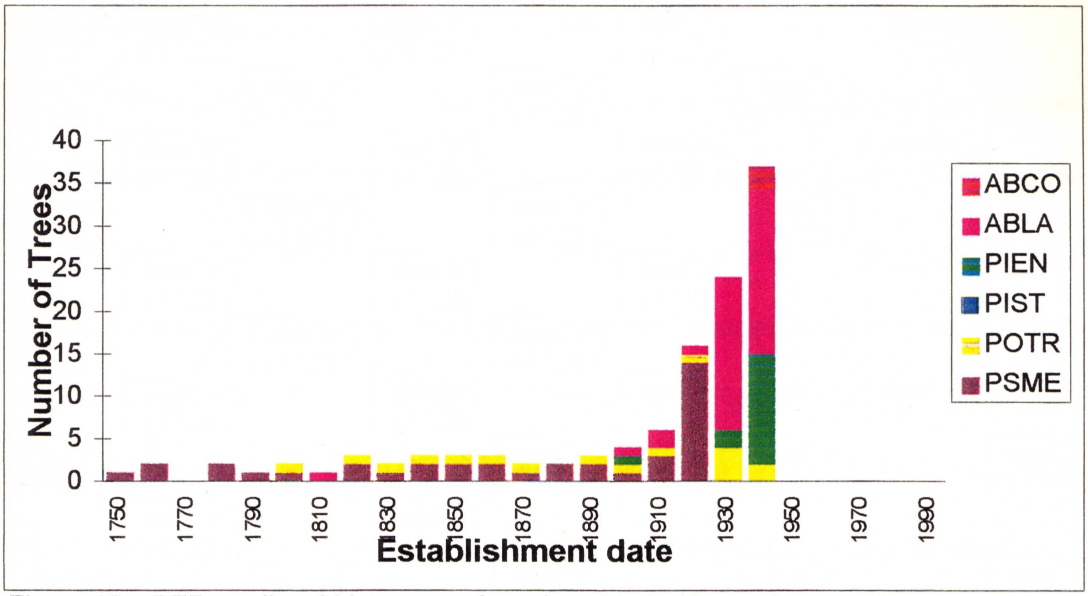


Figure 12a. DFR predicted histogram of survivorship in 10-year increments from DBH/AGE regression equations. ABLA= Corkbark fir, PIST= Southwestern white pine, PIEN= Engelmann spruce, POTR=aspen, PSME= Douglas-fir, ABCO= white fir.

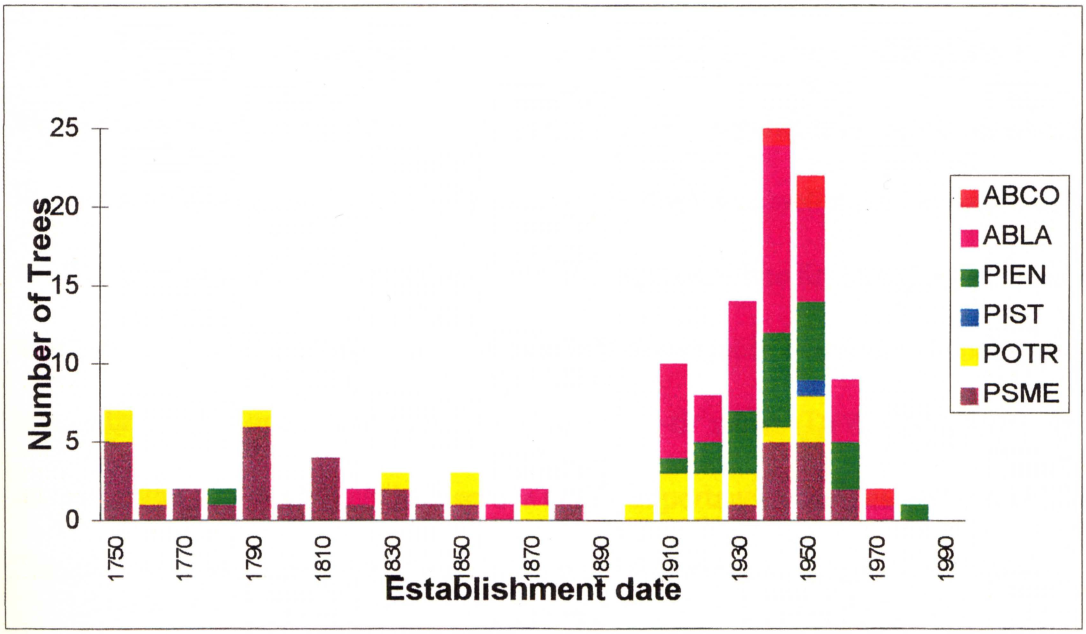


Figure 12a. DFR actual histogram of survivorship in 10-year increments.
ABLA= Corkbark fir, PIST= Southwestern white pine, PIEN= Engelmann spruce, POTR= aspen, PSME= Douglas-fir, ABCO= white fir.

Composition, age, and structure of stands

Histograms of establishment dates (i.e., survivorship) show that later successional species (spruce and true firs) are dominating twentieth century cohorts (Figs. 13a-13e). Frequency charts identify pulses in survivorship (Figs. 14a-14e). Scatter diagrams (dot maps) of tree positions along the transects, generally running from west to east, show spatial arrangement of tree sizes and ages at each site (Figs. 15, 16, 17). Dot maps of tree positions and diameters show size structure arrangement of species (Figs. 15a-15e). Dot maps of tree positions and heights show multiple canopies and gaps in canopies of different tree species (Figs. 16a-16e). Dot maps of tree positions and ages show ages of cohorts (Figs. 17a-17e).

Across all transects, the smallest size classes dominate in number (Tab. 7). Oldest trees in each site differed in species and ages (Tab. 8). Regeneration varied between sites in numbers and species (Tab. 9). Species composition was well mixed in each stand as reflected by importance values (IVs) (Tab. 10). Spruce, white fir, Douglas-fir, pines and aspen were found in all stands. Douglas-fir is codominant in every mixed-conifer and spruce-fir stand. Corkbark fir existed only in spruce-fir stands (DFR, CRK, SPR). The mixed-conifer stands virtually lack spruce (< 2% importance value) as well as corkbark fir. The mixed-conifer stands (ULC and CUB) were dominated by white fir (47-59% importance values) with a strong aspen component (12-14% importance value) and smaller component of pines and Douglas-fir (Tab. 6 and ULC and CUB histograms).

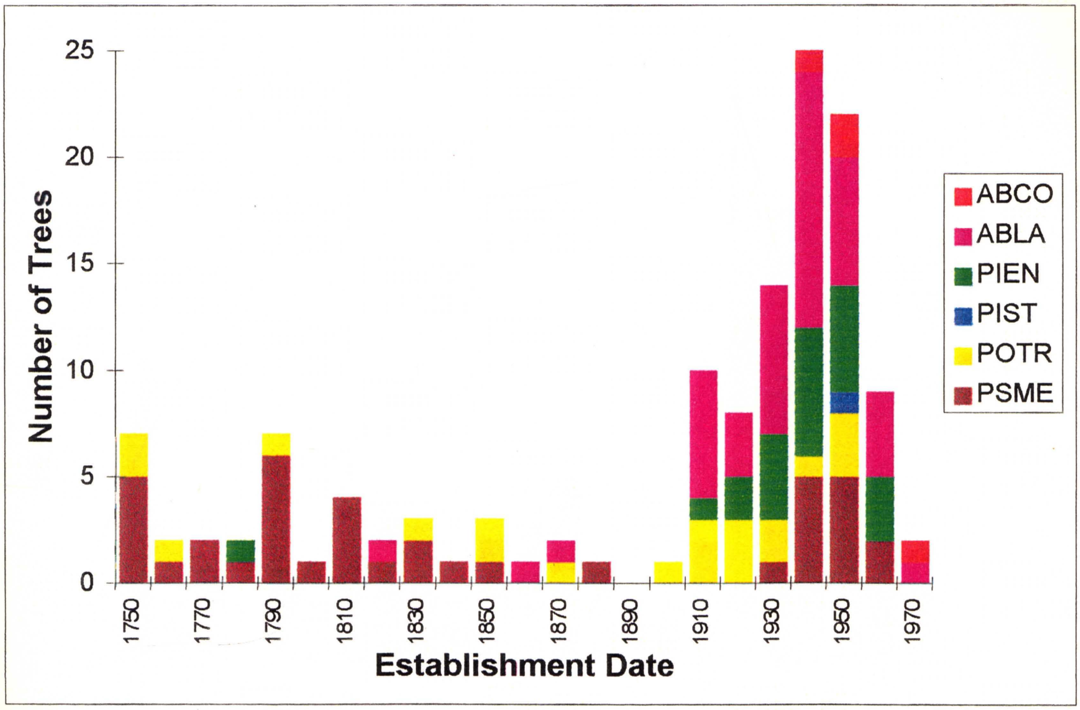


Figure 13a. DFR transect histogram of survivorship in ten-year increments, by species. PSME = Douglas-fir, ABCO = White fir, ABLA = corkbark fir, PIEN = Engelmann spruce, POTR = Aspen, PIST = Southwestern white pine.

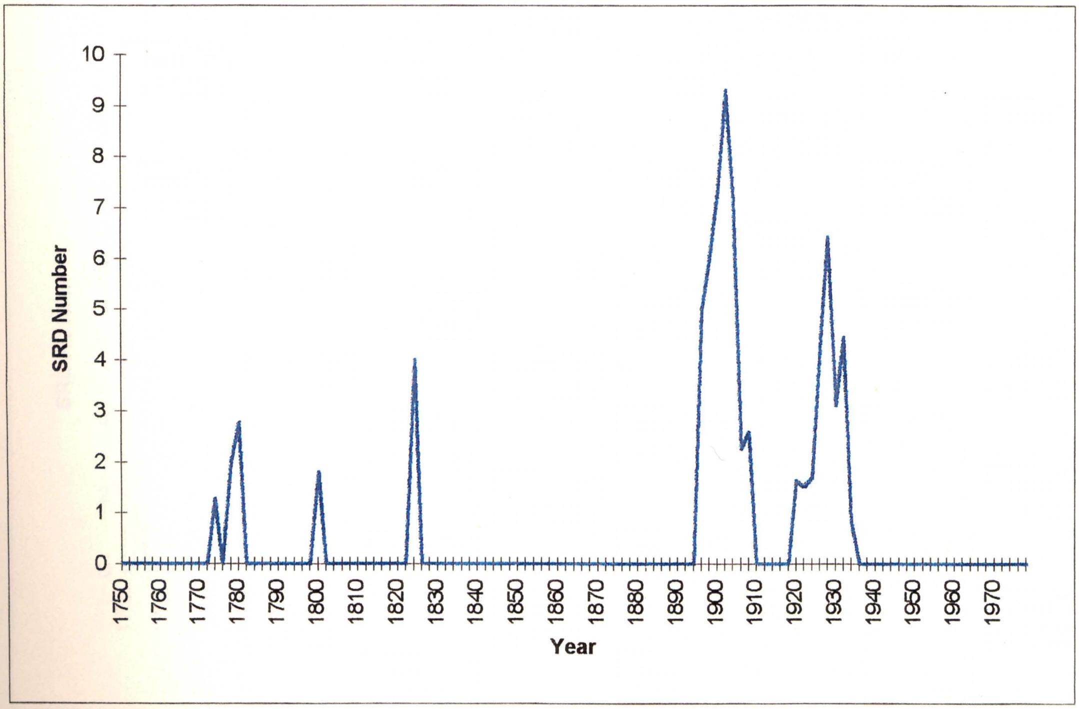


Figure 14a. DFR transect relative survivorship rate difference numbers.

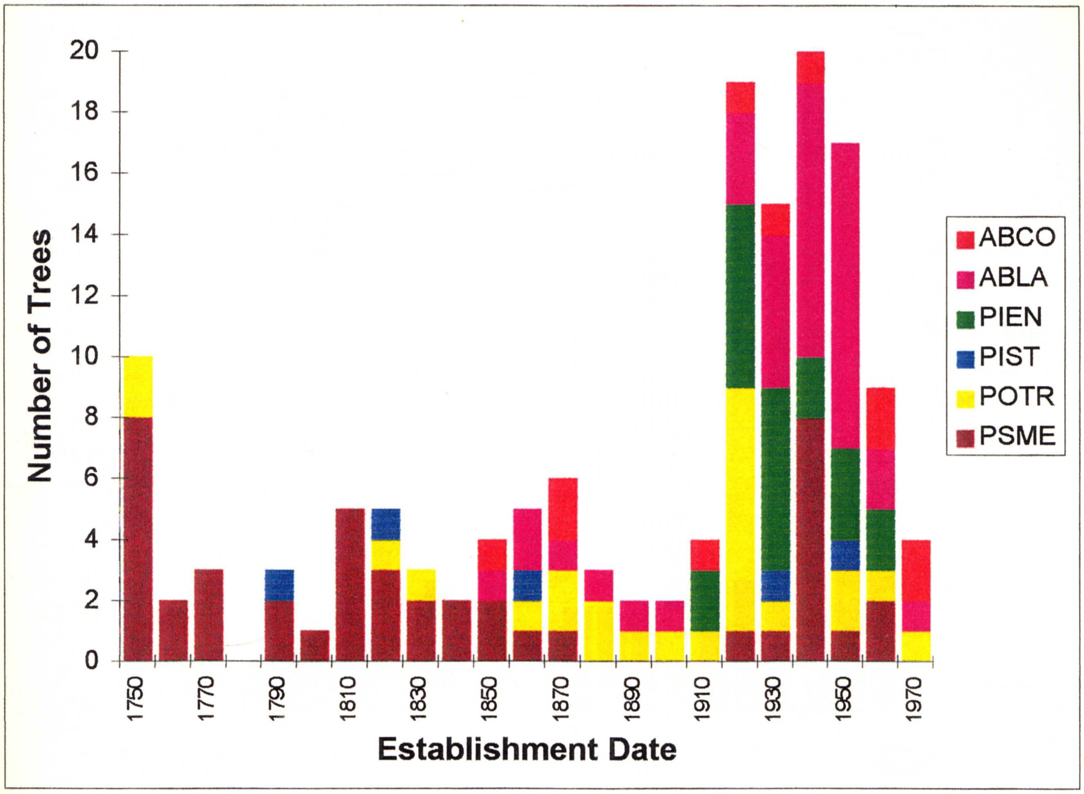


Figure 13b. SPR transect histogram of survivorship in ten-year increments, by species. PSME = Douglas-fir, ABCO = White fir, ABLA = corkbark fir, PIEN = Engelmann spruce, POTR = Aspen, PIST = Southwestern white pine.

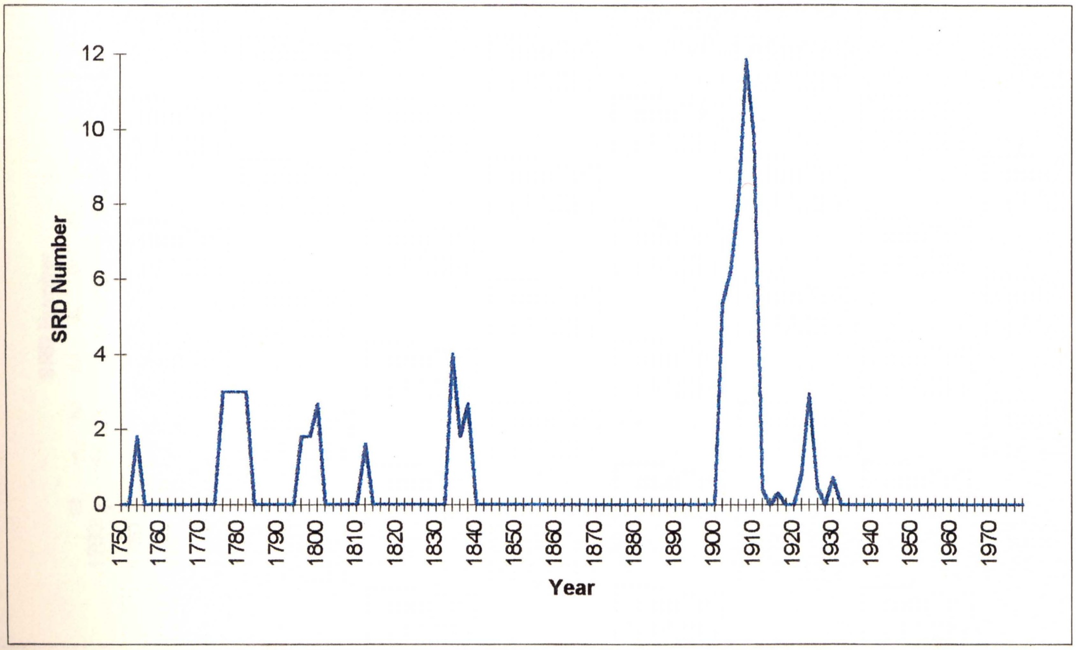


Figure 14b. SPR transect relative survivorship rate difference numbers.

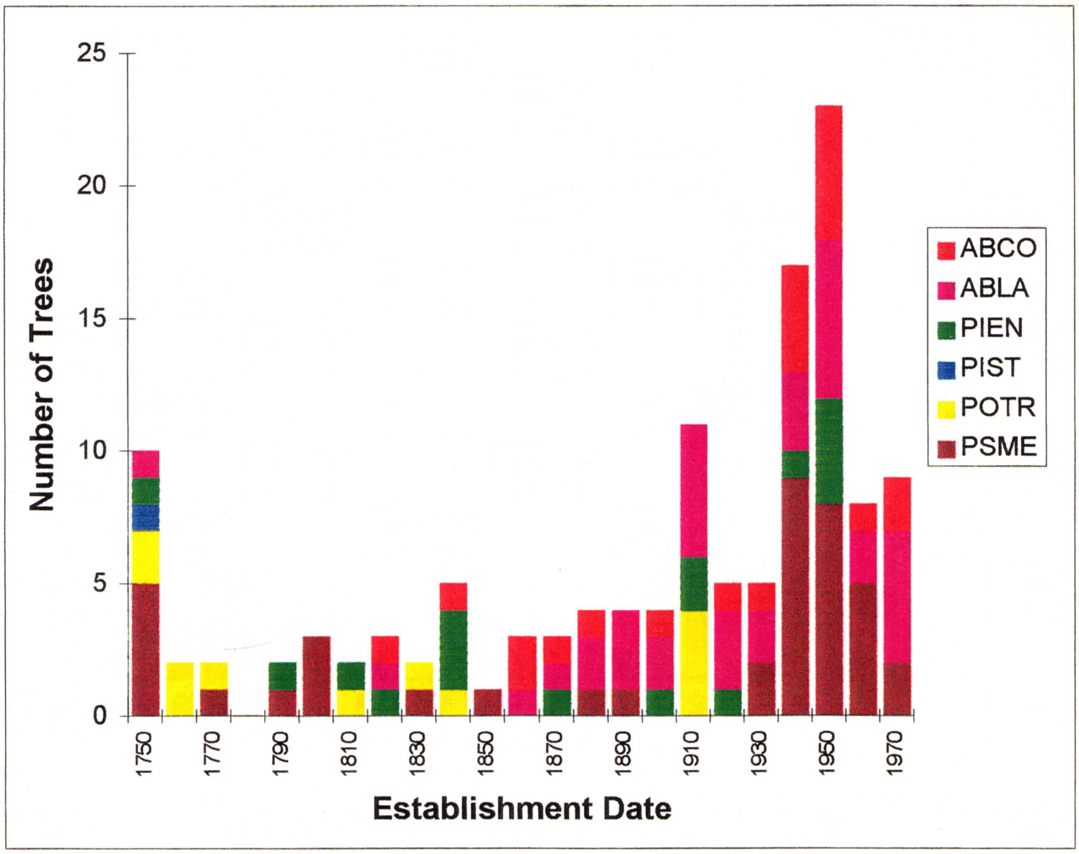


Figure 13c. CRK transect histogram of survivorship in ten-year increments, by species. PSME = Douglas-fir, ABCO = White fir, ABLA = corkbark fir, PIEN = Engelmann spruce, POTR = Aspen, PIST = Southwestern white pine.

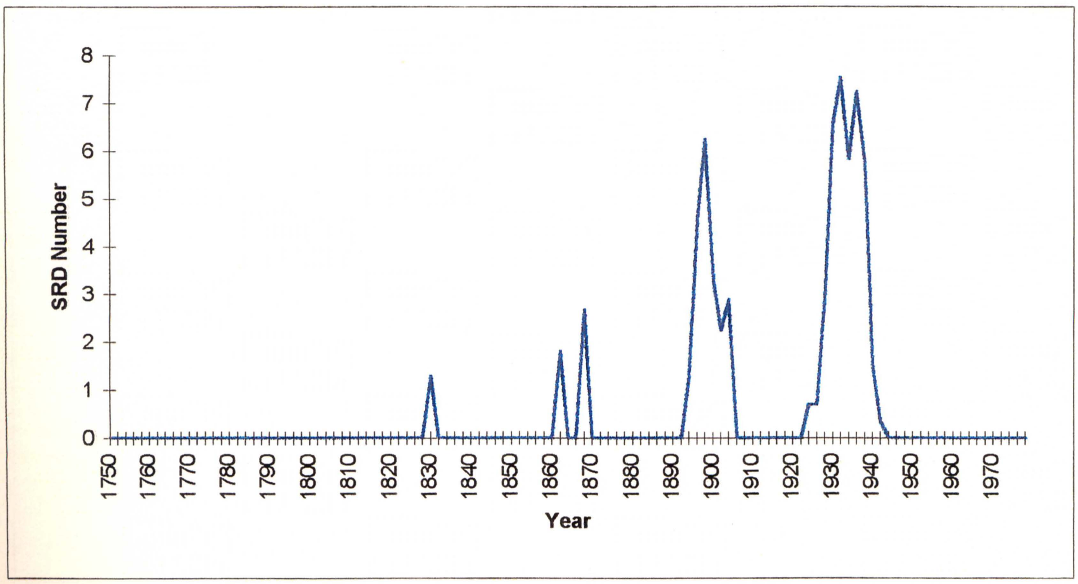


Figure 14c. CRK transect relative survivorship rate difference numbers.

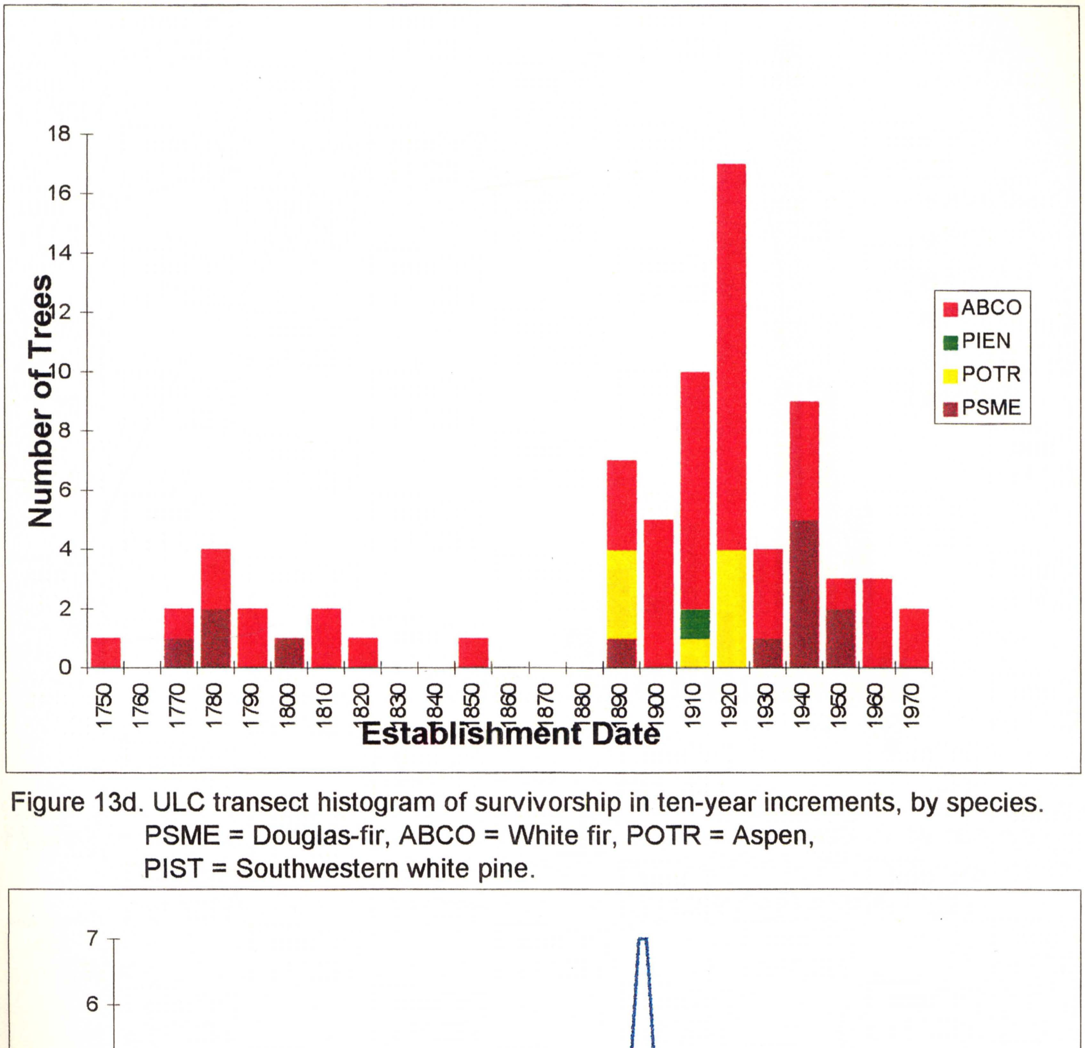


Figure 13d. ULC transect histogram of survivorship in ten-year increments, by species. PSME = Douglas-fir, ABCO = White fir, POTR = Aspen, PIST = Southwestern white pine.

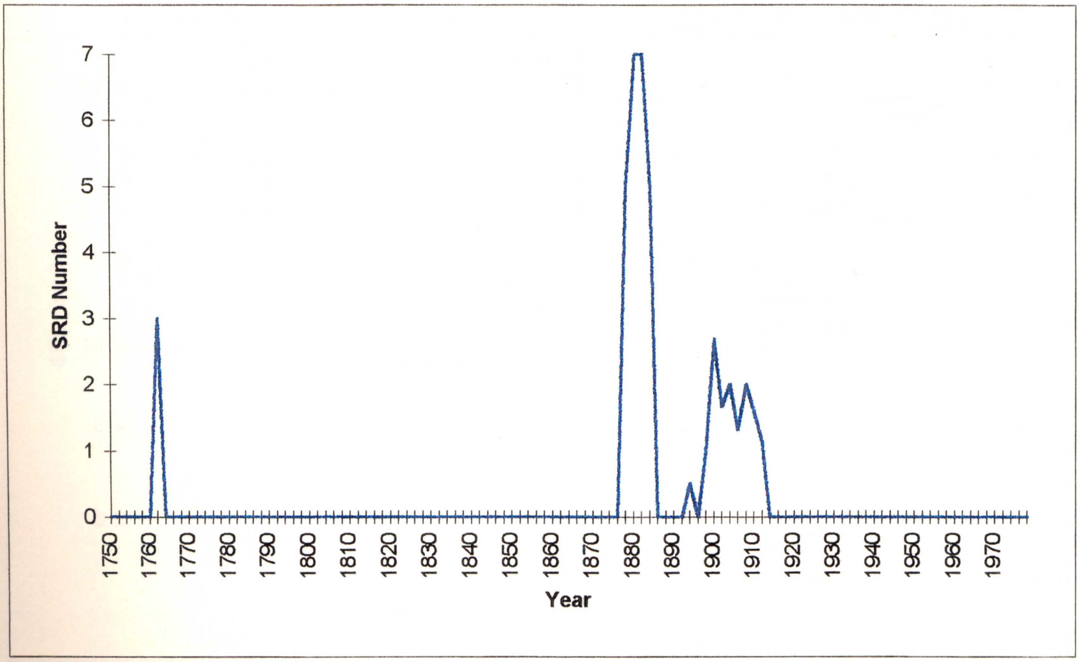


Figure 14d. ULC transect relative survivorship rate difference numbers.

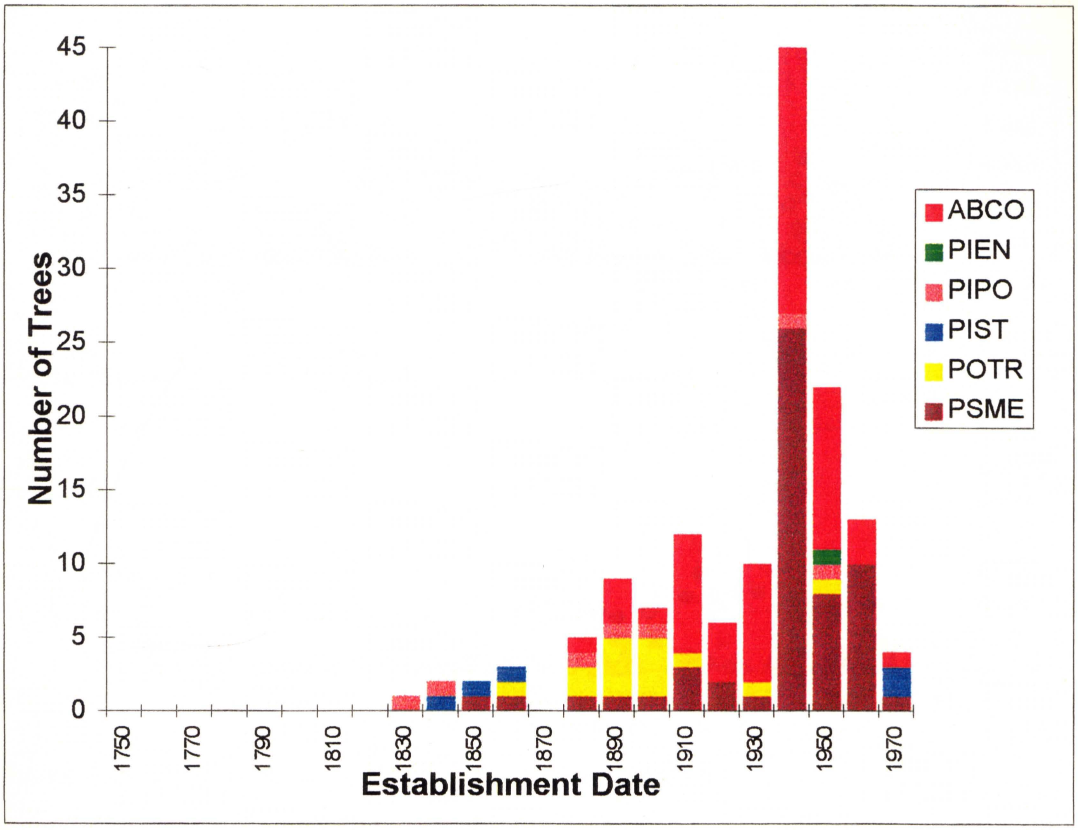


Figure 13e. CUB transect histogram of survivorship in ten-year increments, by species. PSME = Douglas-fir, ABCO = White fir, POTR = Aspen, PIST = Southwestern white pine, PIPO = ponderosa pine, PIEN = Engelmann spruce.

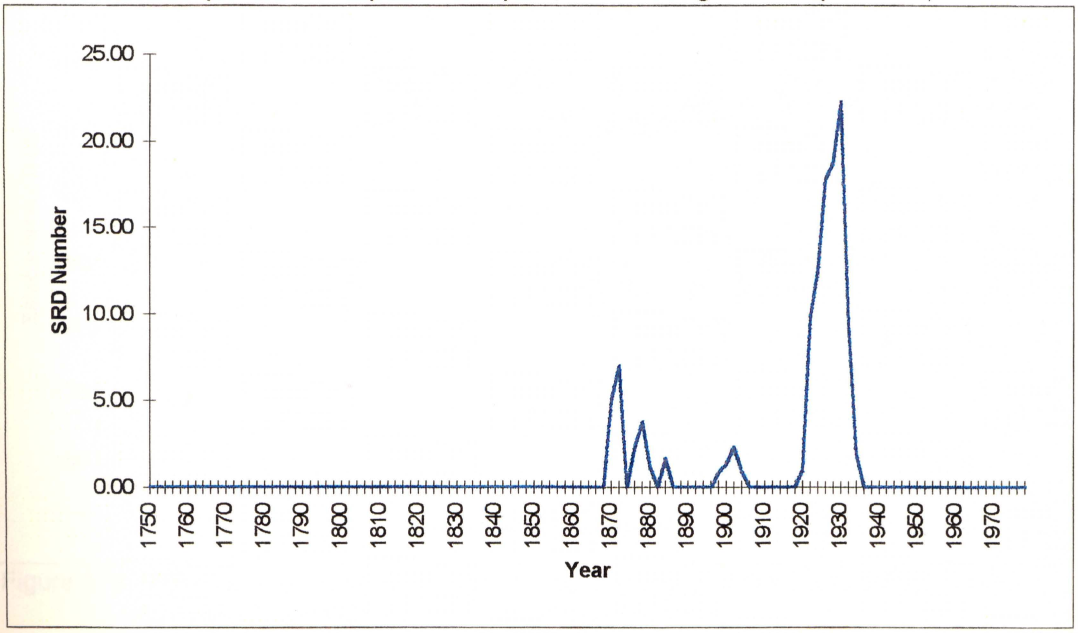


Figure 14e. CUB transect relative survivorship rate difference numbers.

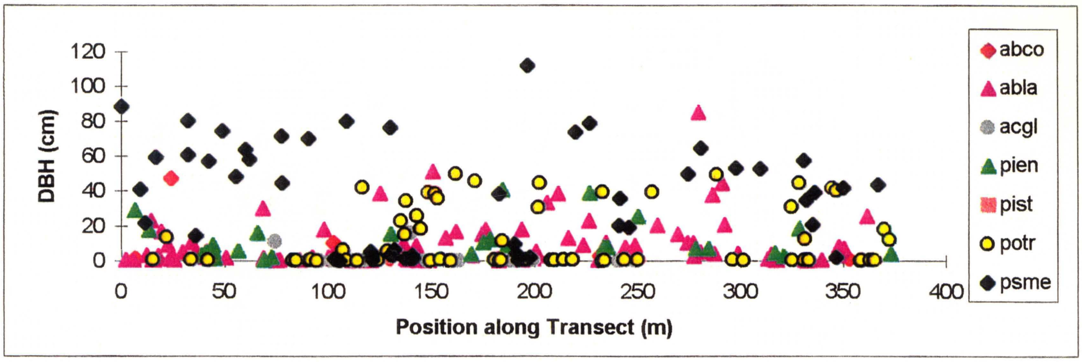


Figure 15a. DFR transect, DBH vs. postion along transect.

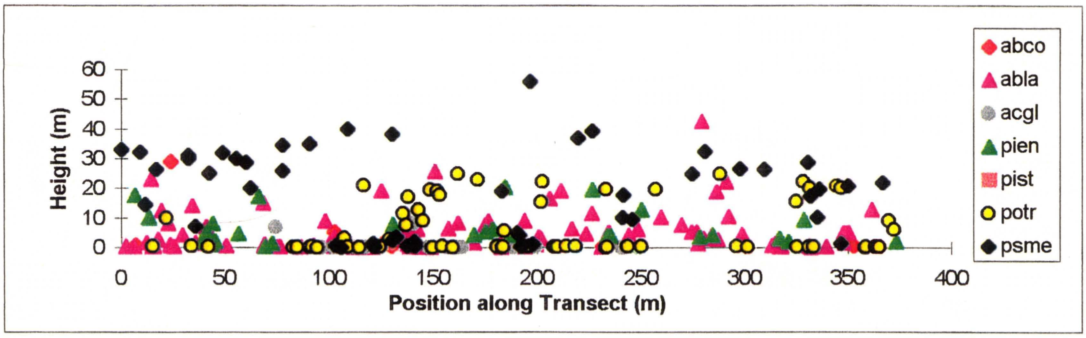


Figure 16a. DFR transect, height vs. postion along transect.

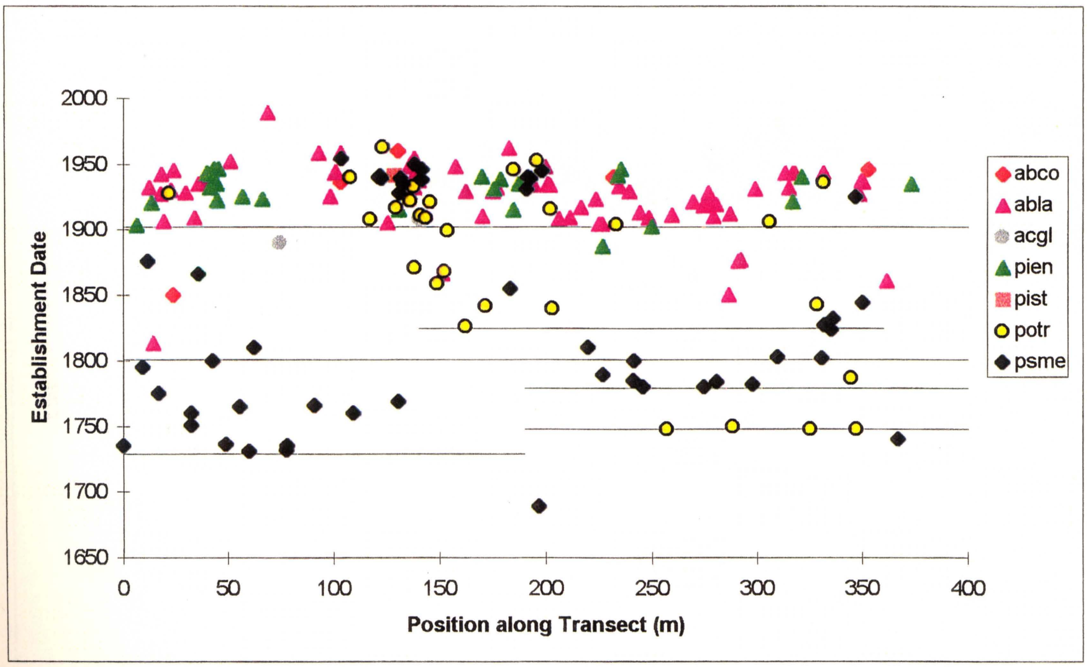


Figure 17a. DFR transect, age vs. postion along transect and fire years identified by survivorship rate difference method and fire scars.

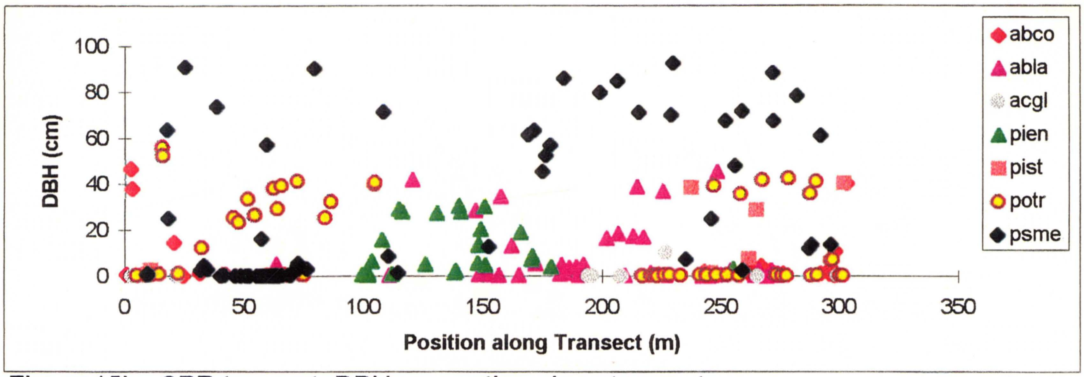


Figure 15b. SPR transect, DBH vs. postion along transect.

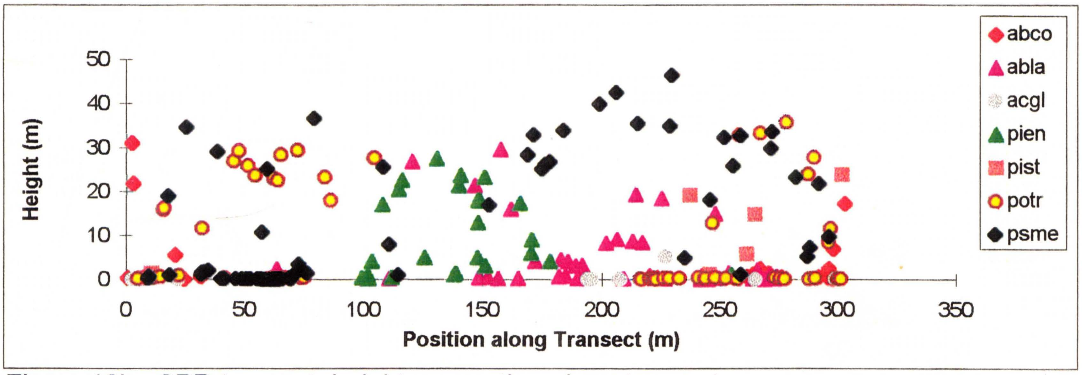


Figure 16b. SPR transect, height vs. postion along transect.

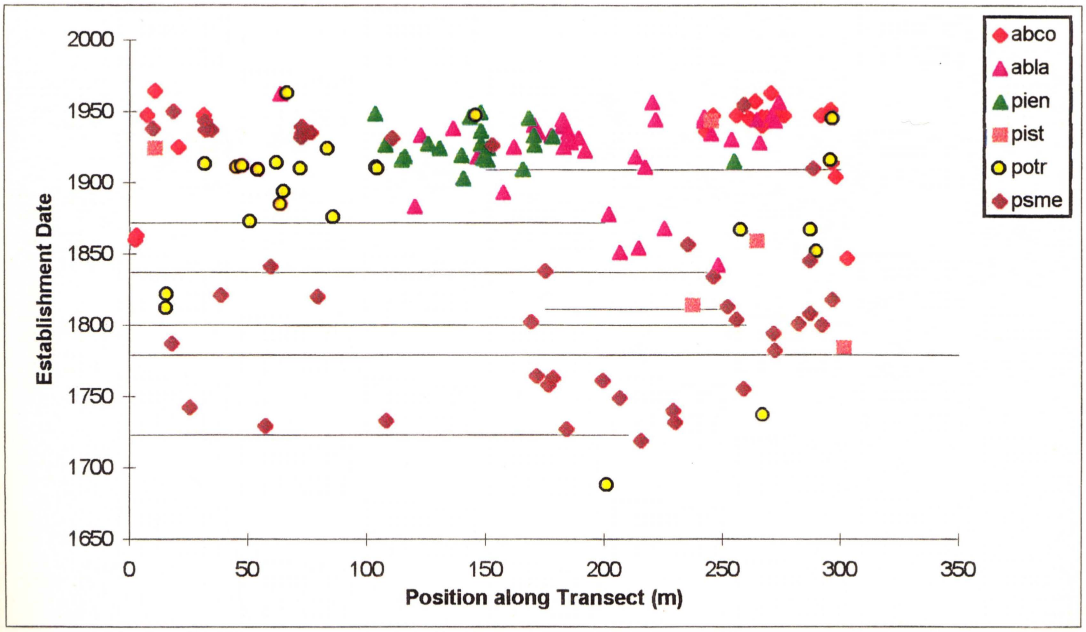


Figure 17b. SPR transect, age vs. postion along transect and fire years identified by survivorship rate difference method and fire scars.

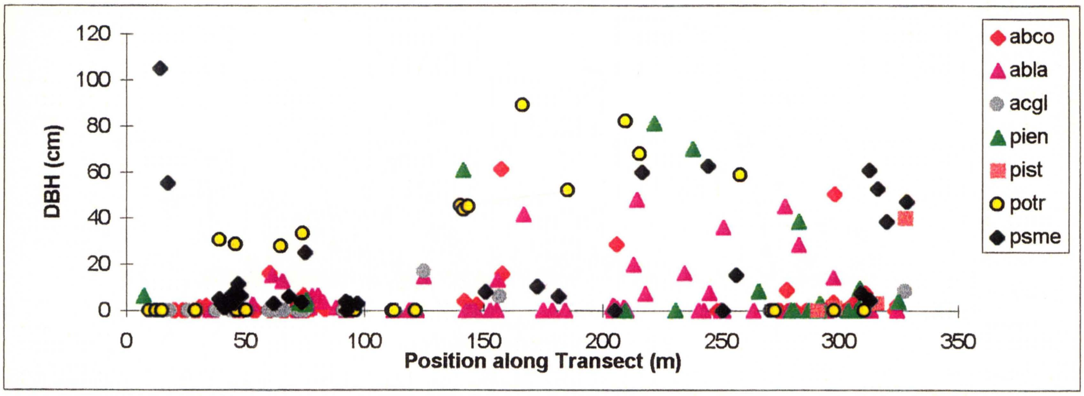


Figure 15c. CRK transect, DBH vs. position along transect.

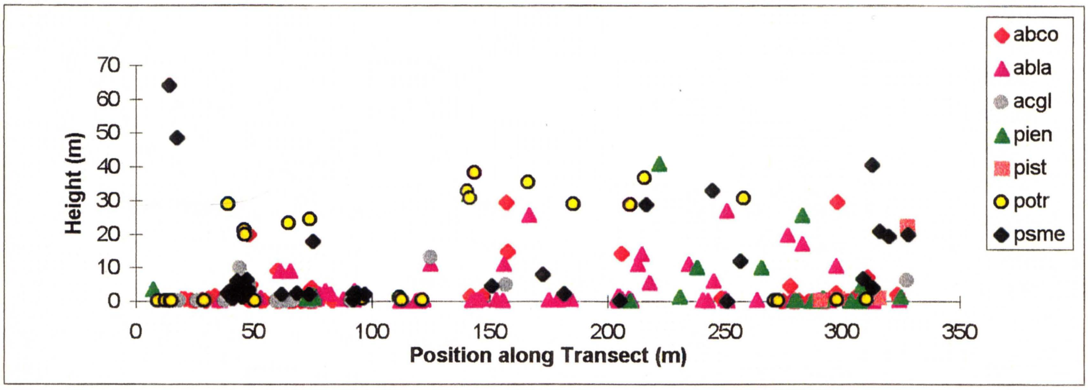


Figure 16c. CRK transect, height vs. position along transect.

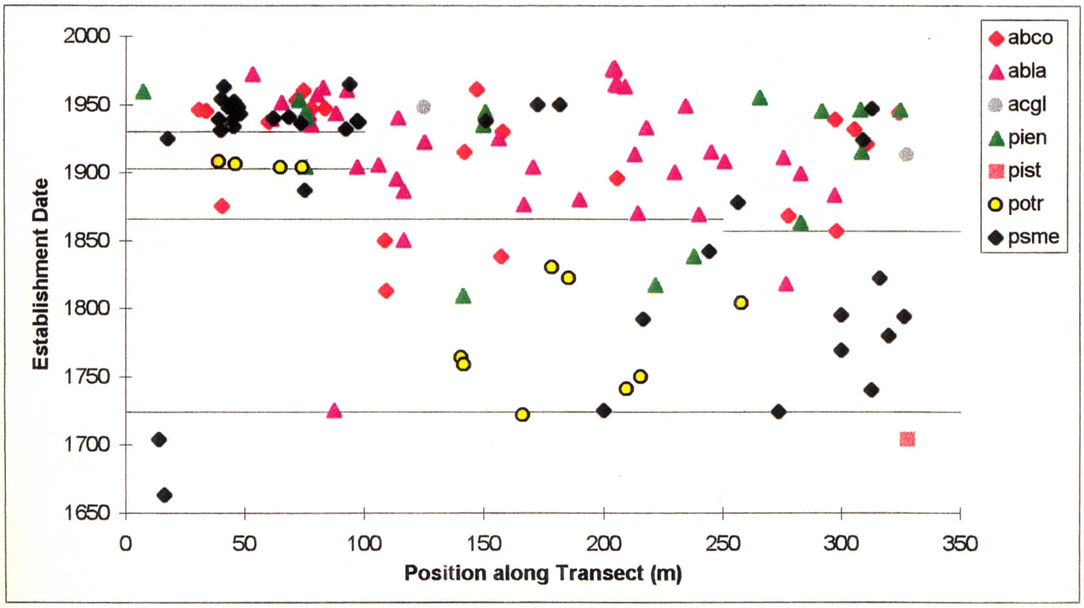


Figure 17c. CRK transect, age vs. postion along transect and fire years identified by survivorship rate difference method and fire scars.

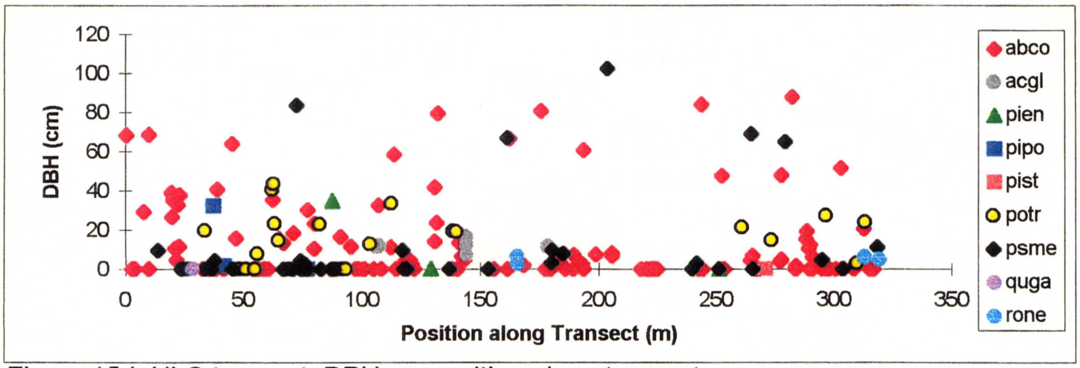


Figure 15d. ULC transect, DBH vs. position along transect.

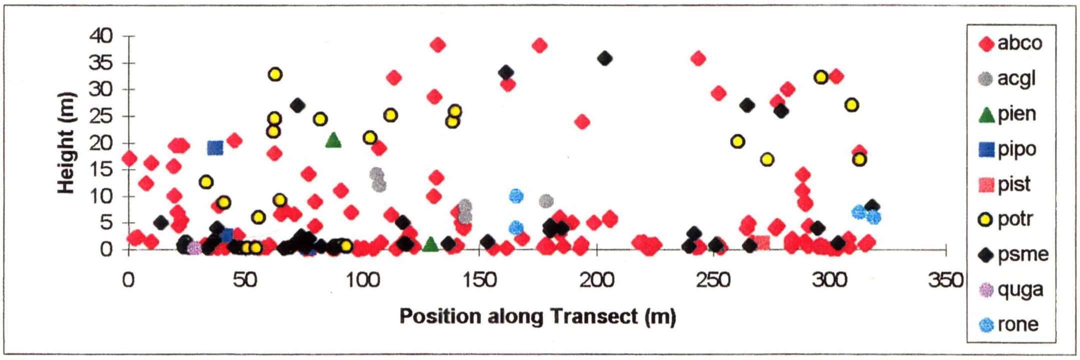


Figure 16d. ULC transect, height vs. position along transect.

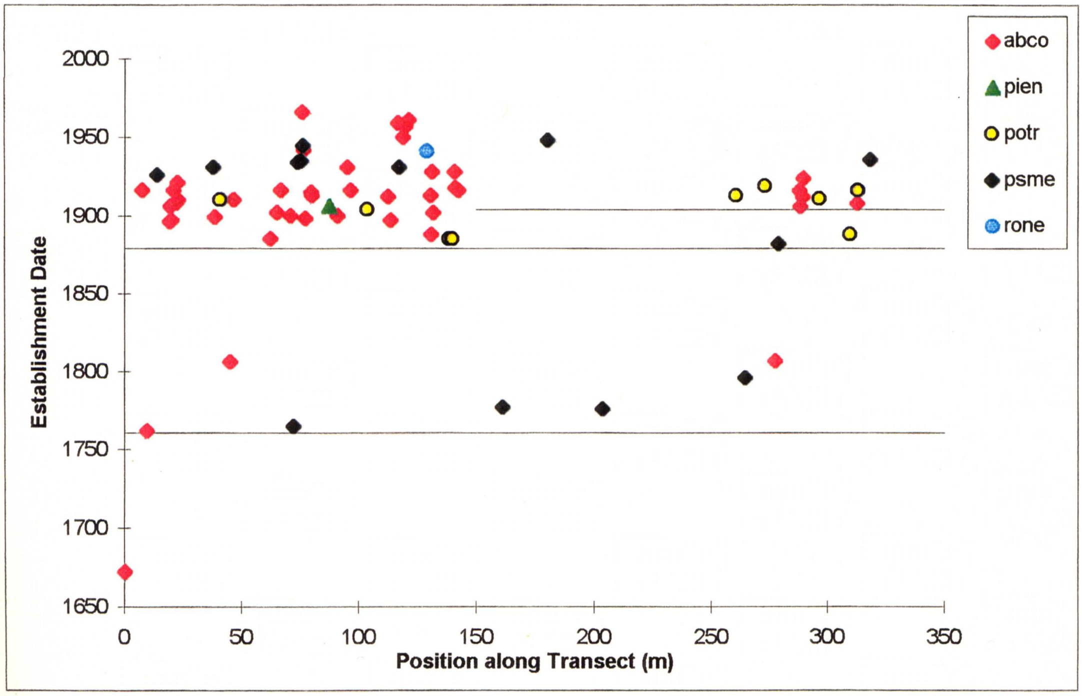


Figure 17d. ULC age vs. position along transect and fire years identified by survivorship rate difference method and fire scars.

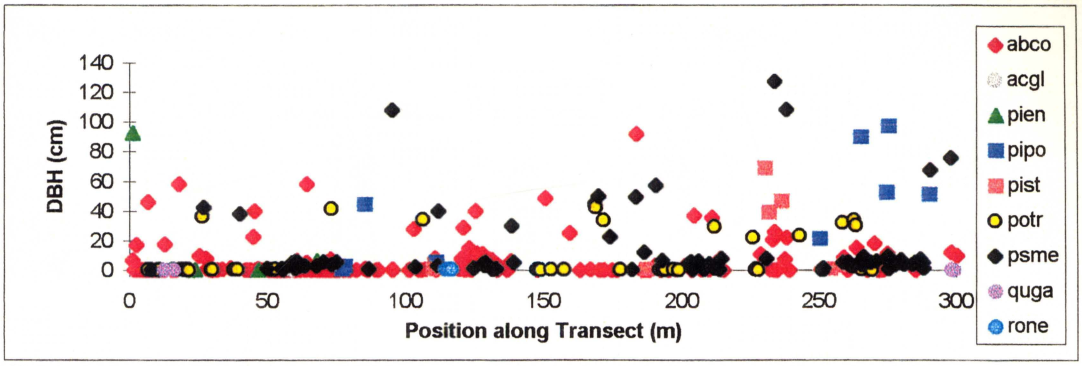


Figure 15e. CUB transect, DBH vs. postion along transect.

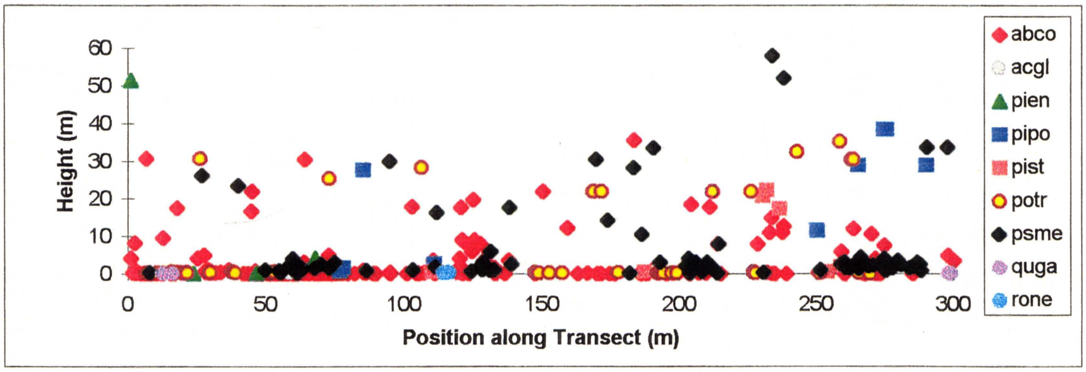


Figure 16e. CUB transect, height vs. position along transect.

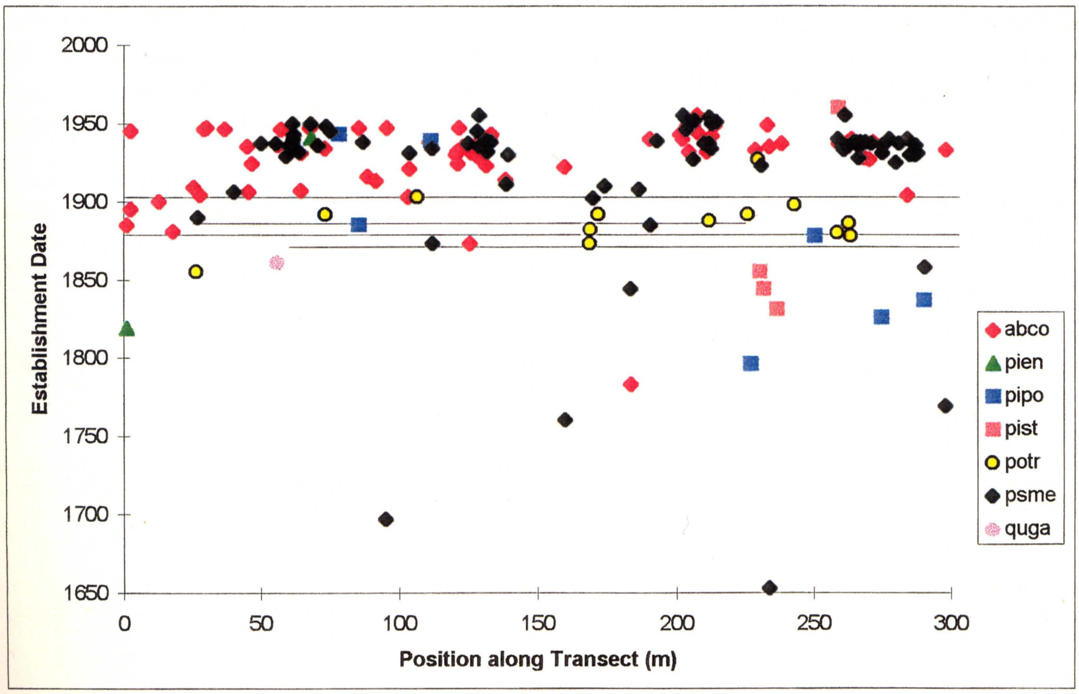


Figure 17e. CUB transect, age vs. postion along transect and fire years identified by survivorship rate difference method and fire scars.

Table 7. Number of trees per DBH size class in each transect.

	< 0.5 cm	0.5-30 cm	30-60 cm	> 60 cm
DFR	118	255	46	14
SPR	294	229	36	21
CRK	354	257	32	17
ULC	139	250	21	19
CUB	972	259	35	16

Table 8. Establishment dates of oldest trees by transect and species. PIEN= spruce, ABLA= corkbark fir, ABCO= white fir, PSME= Douglas-fir, PIPO/PIST= ponderosa and Southwestern white pine, POTR= aspen.

TRANSECT	PIEN	ABLA	ABCO	PSME	PIPO/ PIST	POTR
DFR	1902	1813	1936	1731	1941	1748
SPR	1904	1842	1847	1719	1784	1693
CRK	1694	1750	1818	1840	1704	1750
ULC	1906	N/A	1672	1765	snags	1885
CUB	1941	N/A	1873	1844	1830	1855

Table 9. Number of seedlings by species and site. PIEN= spruce, ABLA= corkbark fir, ABCO= white fir, ACGL= Rocky Mountain maple, PSME= Douglas-fir, PIPO/PIST= ponderosa and Southwestern white pine, POTR= aspen, QUGA= Gambel oak, RONE= New Mexican locust.

Site	ABCO	PSME	POTR	ABLA	PIEN	QUGA	PIST	ACGL	RONE
DFR	2	1	39	34	7			35	
SPR	14	185	41	20	8			26	
CRK	227	5	15	53	11		1	42	
ULC	97	20	16		2	2	2		
CUB	889	57	8			6	5	2	5

A substantial aspen component makes up from about 12 to 19 percent (IV) of all stands. However, the overall basal area of aspen in mixed-conifer stands is roughly half of basal area in spruce-fir stands (Tab. 11).

Basal area of different size classes of each species indicates the development of stand structure for each site (Tab. 11). Smaller size classes generally represent later establishment, while larger size classes represent earlier establishment. Smaller size classes represent future canopies and the trajectory of the forest. Two spruce-fir stands (DFR, SPR) established as smaller size-classed cohorts in the twentieth century under larger size-classed mixed-conifer canopies. Two mixed-conifer forests (CUB, ULC) have remained mixed-conifer throughout the past three centuries, as represented in large and small size classes. One spruce-fir (CRK) stand has remained spruce-fir over the last three centuries, as represented by large and small size classes.

Dead spruce and corkbark fir were found throughout CRK, DFR and SPR, indicating that spruce-fir components are not new to these stands (Tab. 12). Remains of an earlier canopy that included spruce and corkbark fir were found in present-day spruce-fir stands (DFR, SPR and CRK) as logs and snags. The live spruce of DFR and SPR established recently, during the fire suppression era (post 1904). In contrast, the live CRK spruce established throughout the 18^{th} and 19^{th} centuries, and its numbers have substantially increased during the twentieth century fire suppression era. These three stands are considered spruce-fir stands because the spruce and corkbark fir trees make up over 25% (IV) of the stand. However, they are dominated by Douglas-fir (26-42% IV) in the canopy (especially SPR and DFR, Figs 16-17)K).

Table 10. Density, stocking and importance values of trees >0.5 cm DBH.

Transect	Community[1]	Species[2]	Density (stems/ha)	%	Basal Area (m^2/ha)	%	Importance Value[3]
DFR	SF/MC	ABCO	73.3	3.3	1.28	1.3	2.3
		ABLA	877.8	39.4	17.2	17.9	28.6
		ACGL	40.0	1.8	0.39	0.4	1.1
		PIEN	333.3	15.0	5.57	5.8	10.4
		PIST	13.3	0.6	0	0	0.3
		POTR	360.0	16.2	20.31	21.1	18.6
		PSME	531.1	23.8	51.67	53.6	38.7
		TOTAL	2228.8	100.0	96.42	100.1	100.1
SPR	SF/MC	ABCO	291.7	13.0	3.96	3.4	8.2
		ABLA	591.7	26.3	8.5	7.3	16.8
		PIEN	375.0	16.7	8.73	7.5	12.1
		PIST	83.3	3.7	3.2	2.8	3.2
		POTR	330.6	14.7	24.21	20.8	17.8
		PSME	577.8	25.7	67.53	58.1	41.9
		TOTAL	2250.0	100.0	116.28	99.9	99.9
CRK	SF	ABCO	807.7	39.6	13.37	13.4	26.5
		ABLA	448.7	22.0	19.55	19.6	20.8
		ACGL	30.8	1.5	0.51	0.5	1.0
		PIEN	300.0	14.7	7.52	7.6	11.1
		PIST	7.7	0.4	0.98	1.0	0.7
		POTR	123.1	6.0	22.31	22.4	14.2
		PSME	320.5	15.7	35.28	35.5	25.6
		TOTAL	2038.5	100.0	99.51	100.0	100.0
ULC	MC	ABCO	1028.6	55.3	55.71	62.2	58.7
		PIPO	59.5	3.2	7.18	8.0	5.6
		ACGL	128.6	6.9	1.71	1.9	4.4
		PIEN	7.1	0.4	0.74	0.8	0.6
		POTR	278.6	15.0	8.47	9.5	12.2
		PSME	214.3	11.5	15.16	16.9	14.2
		RONE	142.9	7.7	0.66	0.7	4.2
		TOTAL	1859.5	100.0	89.62	100.0	100.0
CUB	MC	ABCO	1860.4	64.1	31.48	28.8	46.5
		PIPO	145.8	5.0	21.1	19.3	12.2
		PIEN	54.2	1.9	2.84	2.6	2.2
		PIST	16.7	0.6	3.98	3.6	2.1
		POTR	493.8	17.0	10.84	9.9	13.5
		PSME	318.8	11.0	38.37	35.1	23.1
		QUGA	12.5	0.4	0.58	0.5	0.5
		TOTAL	2902.1	100.0	109.19	100.0	100.0

[1]SF= spruce-fir, MC= mixed-conifer

[2] PIEN= spruce, ABLA= corkbark fir, ABCO= white fir, PSME= Douglas-fir, PIPO= ponderosa pine PIST= Southwestern white pine, POTR= aspen, RONE= New Mexican locust, QUGA= Gambel oak.

[3] Importance value = the average of density and basal area (Density +Basal Area/2).

Table 11. Basal area in m^2/ha of different size classes (0-30 cm, 30-60 cm, >60 cm) by species and transect site.

TRANSECT	SPECIES[1]	0.5-30 cm	30-60 cm	> 60 cm	Total	Total %
CRK	ABCO	2.46	4.45	6.45	13.37	13.4
	ABLA	6.32	11.49	1.73	19.55	19.6
	ACGL	0.51	0.00	0.00	0.51	.5
	PIEN	0.41	0.91	6.2	7.52	7.6
	PIST	0.01	0.97	0.00	0.98	1.0
	POTR	1.96	12.46	7.88	22.31	22.4
	PSME	2.34	10.89	22.05	35.28	35.4
	TOTAL %	14.1	41.4	44.5		
SPR	ABCO	0.53	3.43	0.00	3.96	3.4
	ABLA	3.37	5.13	0.00	8.50	7.3
	ACGL	0.14	0.00	0.00	0.14	0.1
	PIEN	6.48	2.25	0.00	8.73	7.5
	PIST	1.16	2.04	0.00	3.20	2.8
	POTR	4.97	16.59	2.65	24.21	20.8
	PSME	4.23	11.41	51.89	67.53	58.1
	TOTAL %	18.0	35.1	46.9		
DFR	ABCO	0.12	1.16	0.00	1.28	1.3
	ABLA	7.47	7.23	2.52	17.22	17.9
	ACGL	0.39	0.00	0.00	0.39	.4
	PIEN	3.92	1.65	0.00	5.57	5.8
	POTR	4.56	15.76	0.00	20.31	21.1
	PSME	4.56	19.89	27.22	51.67	53.6
	TOTAL %	21.8	47.4	30.8		
ULC	ABCO	10.71	12.97	32.03	55.71	62.2
	ACGL	1.71	0.00	0.00	1.71	1.9
	PIEN	0.00	0.74	0.00	0.74	0.8
	PIPO	0.00	0.63	6.54	7.18	8.0
	POTR	6.78	1.69	0.00	8.47	9.5
	PSME	0.68	0.00	14.48	15.16	16.9
	RONE	0.66	0.00	0.00	0.66	0.7
	TOTAL %	20.55	17.9	59.2		
CUB	ABCO	12.60	16.11	2.77	31.48	28.8
	PIEN	0.05	0.00	2.79	2.84	2.6
	PIST	0.01	2.41	1.56	3.98	3.5
	POTR	2.86	7.98	0.00	10.84	9.9
	PSME	4.12	11.16	23.09	38.37	35.1
	QUGA	0.58	0.00	0.00	0.58	0.5
	PIPO	1.46	6.55	13.10	21.10	19.3
	TOTAL %	19.9	40.5	43.3		

[1]ABCO= white fir, ABLA= corkbark fir, ACGL= Rocky Mountain maple, PIEN= Engelmann spruce, PIST= Southwestern white pine, PIPO= ponderosa pine, POTR= aspen, PSME= Douglas-fir, QUGA= Gambel oak, RONE= New Mexican locust.

Table 12. Number of large (>30 cm DBH) logs and snags of species in each transect. PIEN= spruce, ABLA= corkbark fir, ABCO= white fir, PSME= Douglas-fir, PIPO= ponderosa pine PIST= Southwestern white pine, POTR= aspen.

SITE	PIEN	ABLA	ABCO	PSME	PIPO/PIST	POTR
DFR	1	11	1	5	0	7
SPR	6	6	0	12	0	6
CRK	2	22	0	7	0	6
ULC	0	0	5	1	4	4
CUB	0	0	4	6	9	1

Species composition has not changed in transects SPR, CRK and DFR. Large (>30 cm dbh) spruce and corkbark fir were present in the pre-suppression era (Tab. 12), however, the relative importance of these species in the pre-settlement stand was probably less than in the present stand. Today spruce and corkbark fir dominate the smaller (younger) size classes (Tab. 11). Older aspen and mixed-conifer species (Douglas-fir, white fir, pines) are less in numbers than younger spruce and corkbark fir that recently established during the fire suppression era (Figs. 13a-13e).

The following are descriptions of the development of each stand as interpreted from basal area of different size classes along transects.

DFR transect

Species dominating the DFR plot in basal area are Douglas-fir (54%), aspen (21%), corkbark fir (18%) and spruce (6%) (Tab. 11). The oldest trees are Douglas-fir (established ca. 1731) and aspen (1748). Corkbark fir arrived later in the early 1800s followed by spruce, white fir and pines in the 1900s. The first 150 m of the DFR transect has a scattered, open upper canopy (over 30 m) consisting of Douglas-fir (established ca. 1730s-1780s) dominating over aspen (established ca. 1750s) and corkbark fir (established ca. 1870s).

The canopy (20-25 m in height) over the eastern two-thirds of the transect is relatively thick. The trees that now constitute the canopy established before 1900. It is dominated by Douglas-fir and aspen over corkbark fir, spruce and white fir. The understory is dominated by corkbark fir with spruce, aspen, and Douglas-fir. Regeneration is aspen, corkbark fir and maple with some spruce.

<u>SPR transect</u>

Species dominating the SPR plot in basal area are Douglas fir (58%), aspen (21%), spruce (8%) and corkbark fir (7%) (Tab. 11). The oldest trees are aspen (established ca. 1693), Douglas-fir (established ca. 1719) and a remnant pine (established ca. 1784).

SPR has a scattered, open upper canopy (over 30 m) dominated by Douglas-fir trees (established ca. 1720-1780s) with older aspen trees (established ca. 1690s-1730s) as a relatively minor component. The relatively thick subcanopy (25-20 m) established after 1900 and is dominated by Douglas-fir and aspen over corkbark fir, spruce and white fir. The understory is dominated by spruce with aspen, Douglas-fir and corkbark fir. Regeneration is mostly Douglas-fir, over aspen, maple, corkbark fir, white fir, and spruce.

<u>CRK transect</u>

Spruce-fir and mixed-conifer species were found in close proximity throughout the history of the CRK stand. Tree species in the CRK plot in basal area are Douglas-fir (35%), aspen (22%), corkbark fir (20%), white fir (13%) and spruce (8%) (Tab. 11). The pine component is <2%, and is represented by one living tree in the canopy. The oldest trees in the stand are Douglas-fir (established ca. 1663), spruce (established ca. 1694) and Southwestern white pine (1704). Aspen arrived in the 1750s, followed by corkbark fir and white fir in the early 1800s (1818 and 1840, respectively).

CRK has 2 canopy levels at 38-40 m and 20-25 m. The lower canopy along the first 80 m of the transect is dominated by aspen trees (established after ca. 1900) and topped by Douglas-fir (>48m) that established in the 1690s. A gap between canopies exists for the following 50 m where no trees over 5 m presently exist. The higher canopy along the eastern two-thirds of the transect is dominated by Douglas-fir over aspen and spruce trees (established ca. 1720s). The spruce component is non-existent in the present subcanopy and understory which are dominated by corkbark fir over aspen, Douglas-fir and white-fir. Regeneration is largely of white fir over corkbark fir with some Rocky Mountain maple, aspen and spruce.

ULC transect

Species dominating the ULC mixed-conifer forest in basal area are white fir (62%), Douglas-fir (17%), aspen (10%) and ponderosa pine (8%) (Tab. 11). The pine component exists only as remnant snags that once made up the overstory now sparsely dominated by a few large white fir and Douglas-fir. The oldest trees in ULC are white fir (established ca. 1672) and Douglas-fir (established ca. 1765). Aspen arrived in the late 1800s followed by spruce after 1905.

One dominant canopy (30-38 m) of white fir, Douglas-fir and aspen traverses ULC. The white fir and Douglas-fir components established from 1760-1810, while the aspen came in at the end of the 1800s. The intermediate canopy (15-20 m) is sparsely dominated by white fir over aspen, and established in the early 1900s. From 150-250 m along the transect no trees were recorded between the ages of 1770 to 1948. Regeneration is largely white fir with some Douglas-fir and aspen.

<u>CUB transect</u>

CUB is dominated in basal area by Douglas-fir (44%) and white fir (36%) with some aspen (12%) (Tab. 11). These components are maintained in all levels of the forest. The oldest trees in CUB are Douglas-fir (established ca. 1690), spruce (1819), ponderosa and Southwestern white pine (established ca. 1830s), aspen (established ca. 1855) and white fir (established ca. 1873).

CUB is multistoried with two upper canopy levels across the transect. A lower canopy of Douglas-fir and white fir trees established (1928-1955) to fill gaps in higher canopies of Douglas-fir, white fir and aspen. Trees in the higher canopies (25-30 m) established in the late 1800s in the western portion of the transect, and the in the mid 1800s in the canopy (30-40) over the eastern half. A lone spruce and Douglas-firs top the canopy at over 50m. White fir dominates the understory over Douglas-fir and aspen. White fir dominates (99.9%) regeneration over a few aspen.

Fire history from survivorship rate differences in stand age structure

Temporal patterns

Dates of fire scars from trees sampled within the mixed-conifer stands (ULC and CUB transects) represent fires that burned in those forests. Since fire scars were absent at all of the spruce-fir sites (DFR, CRK, SPR transects), only fire dates inferred by survivorship rate difference analysis and corresponding to fire scar dates recorded in adjacent fire scar collection sites, were identified as having occurred in these stands (Tab. 13).

Traditional histograms of establishment dates (of trees that survived to date) show evidence of increased survivorship at each site since established ca. 1904 (Figs. 13a-13e). Survivorship rate differences between pre and post survivorship indicate many more survivorship peaks not apparent in static histograms (Figs. 14a-14e).

Matching between highly positive SRD year numbers with fire-scar dates supports the inferences based on SRD method. All years showing high SRD numbers followed within 2 years of previously recorded fire dates in adjacent or nearby fire-scar collection sites, but one. A peak year of maximum survivorship rate difference in 1928 did not correlate with a recorded fire year. Fire years recorded from fire scars that do not coincide with recruitment pulses are considered fire years that did not affect recruitment in the stands.

High intensity fire occurrence

I interpret the years of highest peak differences in survivorship (SRD numbers) across the transects to have followed years of relatively high intensity surface fires (Tab. 13). The severity of these fires was great enough to cause mortality followed by apparent surges in survivorship. These fires probably occurred as surface fires with patches of higher intensity fire, including some crowning that killed prior recruitment and favored survival of subsequent recruitment. The effects of these fires within the study area were variable; some fires only affected portions of the transect (due to fire spread barriers--drainage and trail) and some fires destroyed trees further back in time than others (trees from 1 to 140 years in age). Patchiness of pre-settlement surface fires was especially likely in CRK, since some surviving spruce trees were present in this stand. Adult spruces

Table 13. Fire years, length of transect disturbed and pre-fire establishment gaps along areas of the transect inferred from survivorship rate difference analysis, spatial establishment maps, and dates from fire scars.

TRANSECT and LENGTH	FIRE YEAR	LENGTH DISTURBED (m)	PRE-FIRE ESTABLISHMENT GAP (years)
DFR (375 m)	1729	200	not evident
	1748	150	not evident
	1779	150	30
	1801	375	5-110
	1825	200	20
	1904	375	10-30
SPR (300 m)	1723	210	not evident
	1779	50+	10-40
	1801	250	40
	1811	75	10
	1837	250	20
	1871	200	30-150
	1904	300	10-30
	1909	300	5+
CRK (325 m)	1723	325	not evident
	1857	75	30
	1866	250	15-140
	1904	100	15
	1928	30	50
ULC (350 m)	1761	100	not evident
	1879	350	70
	1904	125	10
CUB (300 m)	1871	250	10-80
	1879	300	8-20
	1886	200	15
	1904	200	5-15

are often killed by even low intensity fires burning around their bases. Patchy high intensity fires that affected mortality and surges in survivorship across at least two transects or initiated aspen stands occurred in 1723, 1748, 1801, 1871, 1879, 1904 and 1953.

Spatial patterns

Dot maps of tree age and position along the transect show spatial distribution of survivorship and mortality, and may indicate fire occurrence, spread and severity across the transect (Figs. 17a-17e). Some fire-scar dates recorded in mixed-conifer stands corresponded with gaps in establishment quantified by survivorship rate difference analyses (Tab. 13). Fire years were overlaid on the map to show where burning may have induced mortality and survivorship across portions of the transect. Fire years showing apparent matches with survivorship (high SRD numbers) were plotted on the graphs (Figs. 17a-17e).

Gaps in survivorship suggest that fires spread through the mixed-conifer and spruce-fir forests and killed young trees that had established in the previous decades (Tab. 13). Because a drainage and a trail constructed at the turn of the century divided the transects, some fires burned only the east or west side of the transect plots. Gaps in survivorship from fire mortality differed on east and west sides of the transect, as fires lagged one another, burning different portions of the transect one year, then other portions years later.

The following are detailed descriptions of my interpretations of fire events and their effects on the sampled stands. Since fire scar dates within the actual transects were obtained only in ULC and CUB, these must be considered "best interpretations" based on the SRD method and matching with fire dates in adjacent sampled stands.

In DFR transect, a fire in 1729 burned the western half of DFR, while fires in 1748, 1779 and 1825 burned the eastern half (Fig. 17a). A fire probably caused mortality across the entire transect in 1801. There appears to be a gap in survivors (establishment dates) in the middle 100 m of the transect from ca. 1700 until 1810s, but this apparent gap may have been caused by the fire in 1801 killing prior evidence of survivorship. The 1904 fire apparently spread across the transect, killing trees up to 30 years old and resulting in a survivorship pulse that led to the establishment of the intermediate canopy.

In SPR transect, the western half of the transect burned more frequently than the eastern half. A fire in 1723 spread across the western half of the SPR transect (Fig. 17b). A fire in 1779 probably killed survivors that had recruited in previous decades along the entire transect. A fire in 1801 burned most the transect before a fire in 1811 which burned a smaller portion of the transect. A fire in 1837 burned the western half of the transect. A fire in 1871 burned the western half of the transect and destroyed all prior survivorship in the middle of the transect (100-175 m) back to a Douglas-fir tree that established in 1729. The 1904 fire may have burned throughout the transect, but its effects were masked by those of the 1909 fire. The 1909 was light enough not to kill some aspen and corkbark fir survivorship since 1871 over the first 200 m of the transect, but did take out trees in the latter 100 m. Survivorship of spruce and corkbark fir are concentrated along a drainage in the middle of the transect after the 1904 and 1909 fires.

In CRK transect a fire in 1723 spread across the transect (Fig. 17c). A fire in 1866 affected the majority of the transect. This fire burned most intensely along the first 100 m of the transect where it killed dominant trees back in time to a Douglas-fir tree that established in the early 1700s. The 1904 fire spread across the transect on the west side of the trail. A disturbance in 1928 killed prior survivorship across the same portion of the transect, but did not spread to affect mortality across the trail. This disturbance has not been confirmed as a fire date by fire scars or Forest Service fire atlases.

In ULC transect, a fire in 1761 burned across the stand, killing trees over 50 years in age (Fig. 17d). A fire in 1879 killed trees that established up to 70 years before it across the transect and created an open area in the middle of the transect. Effects of the 1904 fire on mortality and subsequent survivorship along the eastern half of the transect may be masked by the more intense 1879 fire.

Fewer older trees exist in CUB transect to document early fires from survivorship rate differences in the stand (Figure 17e). Because CUB is not dissected by a drainage or trail, fires in 1871, 1879, 1886 and 1904 spread across the majority of the transect. The 1871 fire left the greatest mark on the forest, killing evidence of survivorship back 80 years in time. Though the 1904 fire was identified by survivorship rate difference analysis, it was not recorded by fire-scarred specimens collected from the stand, although this fire date was recorded at many other locations across the study area and was noted in local newspapers and other historical documents.

DISCUSSION

Variability of historical fire regimes

The historical fire regimes of forests in the Gila Wilderness were mosaics of low intensity surface fires that spread across elevational gradients from ponderosa pine to interior mixed-conifer, and perhaps, occasionally within spruce-fir stands. Numerous localized patches of high intensity fire occurred less frequently and on a smaller scale in the mixed-conifer and spruce-fir, as evidenced by gaps in survivorship, multiple canopy cohorts in mixed-conifer and spruce-fir forests, and aspen stands. The fine-grained matrix of species in the spruce-fir and mixed-conifer forests and the gradations between each stand reflects a diverse fire history. Fire behavior was mixed including surface and crown fires, producing a mosaic of habitats with a variety of forest species dominance patterns.

Although fires did spread along the gradient from the mesas up the ridge to the montane grassland at Snow Park, and beyond, fire return intervals did not vary in a strictly linear fashion across the elevational gradient. Elevation is not the only variable associated with fire frequency. Swetnam and Baisan (1997) reported weak relationships between fire frequency, elevation, and forest type. Topographic position, landscape connectivity, and land-use history often overrode other influences on fire occurrence. Though fires in the Gila Wilderness often spread across all elevations, they rarely spread through all forest types. Variability in forest type and microsite topography determines fuel moisture and fire boundaries that affect fire spread, resulting in different fire frequencies for different forest types.

Though early fire suppression efforts were less effective than today (Pyne 1982, Swetnam 1983), active fire suppression coupled with livestock grazing beginning around 1905 ended the fire regime as it had existed for many centuries. The mean fire return interval between surface fires occurring at any site within the study area across the eastern slope of the Mogollons grew from 3 years in the 18th and 19th century pre-suppression era, to 13 years during the twentieth century fire suppression era. Twentieth century ignitions continued to occur frequently, but generally did not spread extensively across the landscape as they did before. Fires during the fire suppression era (1905 to present) have only affected a small portion of the same amount of land that previously burned one or more times per decade.

The typical peak season of burning has not obviously changed during the twentieth century relative to earlier centuries. Fire scars within the earlywood are consistent with the modern fire season in the Gila Wilderness, with the majority of fires spreading during the dry season before the summer monsoons commence (i.e., approximately May through June).

The last landscape-scale fire year was in 1904. Fires burned the entire eastern face of the Mogollons in a mosaic of different intensities as evidenced by fire scars, aspen stand initiation, and age structure transects spread across a 20 km distance from Hummingbird Saddle to Langstroth Mesa and Cub Mesa. Age structure information also indicates the fires in 1904 affected the mixed-conifer forest on Cub Mesa, although sampled fire scars in the stand did not record the event. Apparently, this fire year was characterized by mixed intensities, burning both as extensive surface fire and as patches of high intensity crown fire. Fire behavior was most extreme in places marked now by aspen. Since changes in fuels due to human actions were probably insignificant at this time, fire behavior in 1904 may be considered "natural" or well within the historical range of variation of fire regimes prior to fire suppression.

The survivorship rate difference analysis identified additional intense fires, some of which affected survivorship to a greater extent than the 1904 fire. These fires induced mortality further back in time across larger portions of the transects sampled (e.g., 1871 fire effects on SPR) (Tab. 13).

Effects of the Lookout fire in 1953 resulted in initiation of aspen stands and the creation of fire scars throughout Snow Park, similar to the 1904 fire. The 1953 fire may have spread throughout a larger area of the Mogollons had it not been suppressed. Another high intensity fire (also called the Lookout fire) occurred in June 1996. Future study on effects of this fire on forests stand composition and age structure should be undertaken to determine if fire severity was historically anomalous. In particular, the size of the high intensity fire-initiated patches should be compared with the pre-existing aspen stands.

Effects of fire and fire suppression on forest succession

Fire suppression has changed the successional trajectory of Gila forests. Fire control has allowed successional processes to proceed further than they otherwise would have without disturbance. In some areas, seventeenth century mixed-conifer stands have succeeded to twentieth century spruce-fir stands. Spruce and corkbark fir have increased substantially in number and size in the stands and remained there due to lack of surface fires since 1904. Stands that were largely dominated by mixed-conifer species are now dominated by spruce and corkbark fir (CRK, DFR, SPR). In some mixed-conifer stands, the once-dominant pine component has been replaced by white fir and Douglas-fir (ULC, CUB).

Aspen

The pure (monospecific) aspen stands cored to determine stand origin followed the typical successional route. Stands of spruce-fir or mixed-conifer were destroyed by fire and replaced by stands of aspen. The oldest aspen stand sampled (GFP) initiated in 1748 and has since been infiltrated by spruce and fir that began establishing in the 1800s. Now, the once dominant, shade intolerant aspen is becoming a minor part of the stand as spruce and fir have taken over the canopy. This is the well-known cycle of succession for aspen, but the uniqueness of this pattern in the Mogollons is the temporal scale. Generally it is believed that aspen begins senescence at about 100 years and may live up to 200 years (Jones and DeByle 1985). However, cores from some aspens in this stand were solid, without heart rot, indicating that these 248 year-old aspen were healthy and may live to considerably older ages. Hence, the aspen replacement cycle is perhaps much longer in the Mogollons than elsewhere in the Rocky Mountains.

A less typical role of aspen is as a minor but persistent component of mixed-conifer or spruce-fir forests. Aspen is codominant in the Douglas/spruce-fir stands and continues to recruit in small openings. Aspen persists as a codominant with Douglas-fir trees in the canopies for hundreds of years, as well as in the understory and on the forest floor as regeneration. Many of the mature aspens survived surface fires that burned within the stands as evidenced by fire-scarred trees sampled nearby. Persistence may have been possible because these surface fire were patchy, and did not always burn immediately around the aspens, and/or because the thick bark of older aspens is somewhat fire resistant.

Past fires had differential effects, as indicated by aspen having remained viable and healthy up to 300 years-old. Fires in the mixed-conifer were mixed surface and understory crown fires of variable intensity and size. Just as mixed-conifer forest was sustainable with surface fires, so was a mixture of aspen within fine-grained mixed-conifer and spruce-fir forests.

Not all aspen stands are purely monospecific (such as LRA). These stands do not have simply interpretable age structures, or can be assigned to single fire initiation dates.

<u>Fine-grained mixed-conifer and spruce-fir</u>

Two mixed-conifer forests (CUB, ULC) have remained mixed-conifer throughout the past three centuries, though later successional species (namely white fir, and some spruce) have been gaining a foothold in the understory during the fire suppression era.

Two Douglas-fir dominated spruce-fir stands (DFR, SPR) established in the twentieth century under conditions once primarily characterized by mixed-conifer canopies as a result of fire suppression. One spruce-fir (CRK) stand has remained spruce-fir over the last three centuries. CRK is the only stand in which living spruce survives as a component of the original canopy established before this century. The spruce and fir are located in a swell that is moist enough to keep most fires out. However, it should not be assumed that spruce and corkbark fir are entirely new components of DFR and SPR. The occurrence of a few dead spruce and corkbark fir, with pre-fire suppression establishment dates, in the spruce-fir stands indicated that these species were present in former canopies, as well.

Past mixed-fire events identified by survivorship rate difference analysis indicated that patchy surface fires may have occurred in spruce-fir forests. The conventional wisdom on fire regimes in spruce-fir forests being primarily of the stand-replacement type is challenged by evidence suggesting that at least some moderately intense patchy surface fires occurred in the Douglas-fir dominated spruce-fir stands. Burning embers from adjacent mixed conifer surface fires can be taken by the wind into spruce-fir to start "spot" fires, killing some trees before dying out. Patchy fires of medium intensities probably occurred that were severe enough to kill recent survivorship but benign enough to not take out all mature spruce and other species in these stands.

Fire in spruce-fir does not always result in a stand-initiating event. Mixed intensity fires occurred in the more diverse Douglas-fir dominated spruce-fir stands. Patchy surface fires in Douglas-fir/spruce-fir forest have allowed aspen, spruce and corkbark fir to persist.

These spruce-fir stands (CRK, DFR, SPR) were surrounded by mixed-conifer and mixed with mixed-conifer species that promote surface fires. In fact these stands were generally what might be classified as mixed-conifer/spruce-fir transition.

Prior to this research it has been assumed that surface fires did not play a role in past spruce-fir fire regimes, because spruce-fir stands generally lack direct evidence of surface fires from fire scars. However, the survivorship rate difference analyses in this fire history study suggests that fires probably burned in some Douglas-fir dominated spruce-fir stands as mixed surface and patchy crown fires several times within a century. This finding is contrary to past fire history studies that estimated the fire return interval for high intensity fires in Southwestern spruce-fir forests at the century-level scale (Abolt et *al.* 1995, Grissino-Mayer et *al.* 1994). These studies examined stationary histograms of survivorship which may have masked survivorship pulses, and thus concluded that spruce-fir stands lacked evidence of surface fire and burned in large crown fires during extensive drought periods at 1-2 century intervals.

This study shows that high intensity fires may have occurred on decadal scales in mixed-conifer and some spruce-fir forests that are dominated by Douglas-fir. The oldest spruce-fir stand (CRK) established itself amidst fires that recurred on a decadal scale as inferred from survivorship rate difference analysis (Tab. 13). The SRD pulses are not explained by climatic reasons, since climate does not vary over a site. The SRD pulses are interpreted as disturbance driven from fire which occurred in patches across the transects; spreading across one side of the transect and not across the other side due to fuel barriers such as drainages and trail. These intense surface fires had crown replacing components that killed prior recruited trees and initiated survivorship of new tree cohorts. These interpretations should not be generalized to spruce-fir forests where Engelmann spruce and white fir are the dominant trees and Douglas-fir is rare or non-existent.

The running histogram method coupled with maps of tree ages and positions along the transect identified fires that affected differences in survivorship rate. The SRD pulses do not prove necessarily that fires occurred, since lack of survivorship could be related to disturbances other than fire (e.g., wind, insect outbreak, etc.). However, correlation with fire years and distinct patchiness of survivorship across all tree species suggest a fire cause. Distinct areas of higher intensity fire probably occurred within many of the more extensive surface burns as represented by gaps in survivorship and different aged canopy patches.

Variability in abrupt spatial impacts on survivorship within and between sites indicated disturbance over climate. Climate is regional and its effects are often expressed locally, but not differently in an abrupt line across trails or drainages. Fires in spruce-fir and mixed-conifer were limited by fuels available at different locations due to forest fuel type, previous fire history, and topographical barriers to fire spread (i.e., drainages, trails, creeks). Natural and human-made topographical features that serve as fire boundaries aided identification of fire effects. Because the age structure transects were dissected by a drainage, many fires could not spread across the entire transect.

Consideration of stand age structure sampling method and analyses

An inherent limitation in static age structures is that they only represent survivorship; trees that survived to the date of data acquisition (June 1994 and 1995).

Despite this limitation, it is still possible to make reasonable interpretations of past stand development from the ages of species represented in the surviving stand, so long as the limitations are recognized.

A change in species composition occurred at the turn of the century due to fire exclusion. The mixed-conifer stands have been increasingly dominated by corkbark fir and Engelmann spruce. This pattern is consistent with a common interpretation of stand dynamics in Rocky Mountain forests: decreased incidence of fire after the turn of the century may have triggered a shift in tree species composition, with reduced importance of Douglas-fir and ponderosa pine and increased importance of more shade-tolerant, but less fire-resistant species (spruce and true fir) (Cooper 1960, Peet 1981).

Analyses of stand structures strongly indicates that spruce and corkbark fir have increased since fire suppression. This inference is strong, but not totally conclusive, as reconstruction of stand dynamics requires determination of mortality rates over time (Johnson et al. 1994). Only a population dynamics approach can provide the information necessary to reach conclusions about species replacements in succession (Johnson et al. 1994). Unfortunately, in the Southwest, where forests are subject to frequent fires, the rates of tree mortality over time are difficult or impossible to estimate because of the removal of dead trees by fires and decay processes.

The limitations of using static age distributions also applies to the SRD measure, because it is difficult to know if low survivorship numbers prior to a year indicate high mortality resulting from the fire, the absence of individuals during that period for other reasons, such as unfavorable climate, or mortality from other causes. Because peak SRD years identified on transect maps were not synchronous across stands, but specific to stands and portions of stands, climate is unlikely to have been a direct cause of these events.

The number of fires identified by the survivorship rate difference method is considered minimum, because not all fires may have been identified by strong SRD numbers because of the sampling design. A different sampling procedure could be employed wherein placement of transects would be in homogeneous areas not dissected by barriers to fire. Fires occurring on different sides of the drainage resulted in different timing of recruitment destruction and subsequent survivorship across the transect plot. Thus, severity of some fires were probably not represented by strong SRD values.

Fire dates fell within 2 years of the SRD suggested date and in some cases probably represented relatively high intensity fire years. However, other fire events occurred that matched fire-scar dates, but were not represented by SRD numbers, because the SRD number was diffused by tree survival in portions of the transect that did not burn (plot location problem). For example, the SRD value was higher for 1904 than for 1801, although effects of the 1801 fire were much greater (canopy trees up to 100 years old were killed). Though the actual intensity of the 1801 fire was high where it burned, the SRD number for 1801 across the transect was low because it did not burn the entire transect. Where a fire did not burn uniformly across the transect then the number of recruits killed by the fire and generated after the fire on one side blended with the continuous survivorship on the other side to cancel each other out. Although the 1871 fire killed trees up to 150 years old, and the 1904 fire destroyed survivorship back only 30 years, the SRD number was less for 1871 than 1904. This is an artifact of sampling along a transect dissected by a fire barrier, and thus crosses two areas with different histories. The SRD number would have been greater if it had been calculated for only the side of the transect. Fortunately, the temporal SRD number coupled with spatial map of survivorship confirmed the magnitude of fire events within the transect plot. A sampling design involving paired line transects located on opposite sides of a fire line would better facilitate survivorship rate difference analysis to identify more fires. The survivorship rate difference method needs to be tested for statistical significance to better quantify the magnitude of fire events from survivorship.

Management implications

Widespread surface fires and patchy crown fires were historically frequent and significant in mixed-conifer forests. The initiation of aspen stands across three centuries indicate that high severity burns were a historical and natural component of the Douglas-fir dominated spruce-fir forest fire regimes. Patchy crown fires occurred throughout the centuries prior to forest management to create the fine-grained complexes of spruce-fir and mixed-conifer studied in the Gila Wilderness. The diversity of fire behavior with moderately intense surface and crown fires killing some earlier cohorts to be replaced by a post-fire cohort results in a variable expression of forest structure and composition. Forests that once sustained surface and crown fires frequently in the past, have been starved of fire. Without fire these forests have become more dense and spatially homogeneous and more at risk to stand replacement fire. Patches of fine-grained complexes such as the heterogeneous mixed-conifer and spruce-fir stands along

Langstroth Ridge are at a great risk from catastrophic fire fueled by unnaturally high fuel build up due to fire suppression.

Reestablishing and perpetuating aspen populations and spruce-fir stands requires that stand-initiating burns be incorporated into the prescribed fire program for upper elevation forests. Along with the goal of frequent surface burning, fire management planners should permit patches of stand-initiating fires in plans for upper elevation forest restoration. The appropriate size distribution of these patches is undetermined at this time, but future studies of aspen stand size distributions could provide an estimate. Given the need for aspen restoration and fuel reduction on a large scale, prescribed burns should be of variable intensities to include stand replacement and of broadcast size to simulate large fires of past and reduce fuels across the landscape. Due to the effects of high intensity fire in areas of high fuel loading, such as soil sterilization and subsequent soil movement and/or stream sedimentation, smaller-scale fuel management burns should precede ecological and watershed management burns for control purposes. Though short-term risk is involved, long-term sustainability of the forest and watershed will be enhanced and risk of catastrophic wildfire is decreased.

The Gila Wilderness is managed under the Wilderness Act mandate "to restore natural conditions and processes." To accomplish this goal in upper elevation forests requires fire. Fire is necessary to the rehabilitation and maintenance of native species and communities dependent on pyric upper elevation forests. Wherever possible (wherever human lives are not threatened) fires must be allowed to spread to historical extents.

Wherever intense fire threatens desired social or ecological values, such fires can be prevented. The best way to prevent high intensity wildfires is to prescribe lower intensity controlled burns to reduce fuels.

Because more fire is required for restoration of sustainable (presettlement) forest conditions than has been allowed to occur across the land this century, managed fires must be extensive throughout all upper elevation forest types. High intensity prescribed burns are necessary for ecological restoration of aspen. To pave the way to lightning-ignited fires, low-intensity planned fires are necessary where fire hazard threatens areas deemed incompatible with high intensity fire (Swetnam 1983).

Though more prescribed burning is sorely needed, efforts to facilitate prescribed fire are not supported like suppression efforts (i.e., with unlimited funds checks from the government to put the fires out). More funding for prescribed fire must be allocated for it to be successfully applied on a large scale. Though some prescribed fires may behave as wild fires, they are not treated or viewed in the same way. Wildfires are viewed as natural acts and nature's own responsibility, while prescribed fires are considered human acts and under human responsibility. For example, prescribed fires that produce large amounts of smoke and ash into the air and stream channels are in violation of the Clean Air and Endangered Species Acts, while wildfires are not. This illogical situation is untenable if we are to learn how to live with the natural fires that are essential for sustaining forest ecosystems.

This research supports prescribed burning efforts in upper elevation forests by showing that some patches of high intensity fire occurred along with extensive surface fire throughout recent centuries. To restore these fires to their historical role, managed fires must be allowed to burn throughout upper elevation forests at every intensity, on scales that are sustainable to overall watershed management. Caution, however, must be exercised throughout the restoration process, because anomalous fuel loadings could result in high-intensity patches that are too large for sustainability.

During the twentieth century, fire occurrence and spread in the study area has decreased. Though fires were generally frequent throughout the pre-fire suppression era, one period (1811-1837) represents a fire free interval of 26 years. In the twentieth century, the mechanisms that allowed trees to sustain fires after 26 years of direct succession, are being tested. Can these forests withstand fires fueled by decades of dead vegetation? Future study on the effects of suppressed fires that occurred in 1953 and 1996 (the Lookout fires) may answer whether or not these fires were within the range of historical variability and should have been allowed to burn. Though fires historically burned extensively in the upper elevations, effects of unmanaged wildfires today may not fall within the range of natural variability.

LITERATURE CITED

Abolt, R.P., M.C. Wilkinson, C.H. Baisan and T.W. Swetnam 1995. Fire history along an elevation transect in the Mogollon Mountains, Gila National Forest. Bulletin of the Ecological Society of America Volume 76, No. 3.

Abrams, M.D., D.A. Orwig and T.E. Demeo. Dendroecological analysis of successional dynamics for a presettlement-origin white-pine-mixed-oak forest in the southern Appalachians, USA. Journal of Ecology 83:123-133.

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington D.C. 493 pp.

Ahlstrand 1980. G.M. Fire history of a mixed conifer forest in Guadalupe Mountains National Park. In Proceedings of the Fire History Workshop, October 20-24, 1980, Tucson, Arizona(eds. M.A. Stokes and J.H. Dieterich). USDA Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report RM-81.

Allen, C.D. 1989. Changes in the landscape of the Jemez Mountains, New Mexico. Ph.D. dissertation, University of California, Berkeley. 166 pp.

Allen, L.S. 1995. Fire management in the Sky Islands. In: Biodiversity and management of the Madrean Archipelago: the sky islands of Southwestern United States and Northwestern Mexico. USDA Forest Service. Rocky Mountain Forest and Range Experiment Station. General Technical Report RM-GTR-264.

Applequist, M.B., 1958. A simple pith locator for use with off-center increment cores. Journal of Forestry 56:141.

Bahre, C.J. 1991. A Legacy of Change: Historic human impact on vegetation of the Arizona Borderlands. University of Arizona Press, Tucson, AZ. 231pp.

Baisan, C.H. and T.W. Swetnam 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research 20:1559-1569.

Baker, W.L. 1992. The landscape ecology of large disturbances in the design and management of nature reserves. Landscape Ecology 7:181-194.

Baker 1994. Restoration of Landscape structure altered by fire suppression. Conservation Biology 8(3)763-769.

Barrows, J.S. 1978. Lightning fires in southwestern forests. Final report, Northern Forest Fire Laboratory, Intermountain Forest and Range Experiment Station and Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colorado. 154 pp.

Bell, W.A. 1870. New Tracks in North America. 2nd Ed. 2 Vols. London: Chapman and Hall.

Bourke, J.G. 1891. On the Border with Crook. New York: Charles Scribner's Sons. 508 pp.

Cooper, C.F. 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. Ecological Monographs 30:129-164.

Covington W.W and M.M. Moore 1994. Southwestern ponderosa forest structure changes since Euro-American settlement. Journal of Forestry 92:39-47.

Dieterich, J.H. 1980. The composite fire interval - a tool for more accurate interpretation of fire history. In Proceedings of the fire history workshops, October 20-24, Tucson, Arizona. USDA Forest Service General Technical Report RM-81:8-14.

Dieterich, J.H. 1983. Fire history of southwestern mixed conifer: a case study. Forest Ecology and Management 6:13-31.

Dieterich, J.H. and T.W. Swetnam 1984. Dendrochronology of a fire-scarred ponderosa pine. Forest Science 30(1):238-247.

Douglass, A.E. 1941. Crossdating in dendrochronology. Journal of Forestry 39(10):825-831.

Dye, A.J. and W.H. Moir 1977. Spruce-fir forest at its southern distribution in the Rocky Mountains, New Mexico. The American Midland Naturalist 97:133-147.

Ferguson, H.G. 1927. Geology and ore deposits of the Mogollon mining district, New Mexico: US Geological Survey Bulletin 922-M. 122 pp.

Fritts, H.C. 1976. Tree Rings and Climate. London: Academic Press. 567 pp.

Fritts, H.C. and T.W. Swetnam 1989. Dendroecology: a tool for evaluating variations in past and present forest environments. Advances in Ecological Research 19:111-188.

Giles, J.S. 1970. Mogollon, the ghost town that refuses to die. Valley News Press, Anthony, New Mexico. 148 pp.

Grant Soil and Water Conservation District 1992. 125 years of records (Ft. Bayard Precipitation). Black Range Resource Conservation and Development Council publication. Silver City, New Mexico.

Grissino-Mayer, H.D., C.H. Baisan, T.W. Swetnam 1995. Fire history in the Pinaleno Mountains of Southeastern Arizona: effects of human-related disturbances. Pages 399-407 in DeBano, L.F., P.F. Ffolliott, A. Ortega-Rubio, G.J. Gottfried, H.R. Hamre, and C.B. Edminster (technical coordinators) Proceedings of the Symposium on Biodiversity and Management of the Madrean Archipelago: The Sky Islands of Southwestern United States and Northern Mexico. USDA Forest Service, General Technical Report RM-GTR-264, Fort Collins, Colorado.

Grissino-Mayer, H.D. 1995. Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. Ph.D. dissertation, The University of Arizona, Tucson. 407 pp.

Holling, C.S. 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. Ecological Monographs 62(4):447-502.

Holmes, R. 1983. Computer assisted quality control in tree-ring dating and measurement. The Tree-Ring Bulletin 43:69-78.

Johnson, E.A. and S.L. Gutsell 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25:239-287.

Johnson, E.A., K. Miyanishi, and H. Kleb 1994. The hazards of interpretation of static age structure as shown by stand reconstructions in a *Pinus contorta-Picea engelmannii* forest. Journal of Ecology 82:923-931.

Johnson, E.A. and G.I. Fryer 1989. Population dynamics in lodgepole-Engelmann spruce forests. Ecology 70:1335-1345.

Johnson, M. 1995. Changes in Southwestern Forests: Stewardship Implications. USDA Forest Service, Southwest Regional office, Albuquerque, NM. 6 pp.

Jones, J.R. 1974. Silviculture of southwestern mixed conifers and aspen: the status of our knowledge. USDA, Forest Service, Rocky Mountain Forest and Range Experiment Station. Research Paper RM-122. 44 pp.

Jones, J.R. and N.V. DeByle 1985. Fire. Pages 77-86 in: DeByle, N.V. and R.P. Winokur, editors, Aspen: Ecology and Management in the Western United States.

USDA Forest Service Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO. General Technical Report RM-119.

Jones, F.R., M.R. Kaufmann, and E.A. Richardson 1985. Effects of water and temperature. Pages 71-76 in DeByle, N.V. and R.P. Winokur, editors, Aspen: Ecology and Management in the Western United States. USDA Forest Service Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO. General Technical Report RM-119. Pp. 77-86.

Kaib, J.M., C.H. Baisan and T.W. Swetnam 1996. Anthro-enhanced fire regimes: "anthropogenic overkill?". Paper presented at the 19th Annual Meeting of the Society of Ethnobiologists. In press.

Kaufmann, M.R., R.T. Graham, D.A. Boyce, JR, W.H. Moir, L. Perry, R.T. Reynolds, R.L. Bassett, P. Mehlhop, C.B. Edminster, W.M. Block and P.S. Corn 1994. An ecological basis for ecosystem management. USDA Forest Service General Technical Report RM-246. Rocky Mountain Forest and Range Experiment Station and Southwestern Region, Forest Service, USDA. 19 pp.

Kellogg, R.M., S. Rowe, R.C. Koeppen and R.B. Miller 1982. Identification of the wood of the soft pines of western North America. IAWA Bulletin. 3(2)95-101.

Kukachka, B.F. 1960. Identification of coniferous woods. Tappi Vol. 43, No. 11 pp. 887-896.

Leopold, A. 1922. Whitewater Fire June 20, 1922. Leopold's Willow Mountain Diary. On file at the Gila Cliff Dwellings National Monument Library.

Leopold, A, 1924. Grass, brush, timber and fire in southern Arizona. Journal of Forestry 22:1-10.

Madany, M.H. and N.E. West 1983. Livestock grazing-fire regime interactions within montane forests of Zion national Park, Utah. Ecology 64:661-667.

McClaran, M.P. and J.W. Bartolome 1989. Fire-related survivorship in stagnant Quercus douglasii populations. Canadian Journal of Forest Research, 19:580-585.

McClaran, M.P. and J.W. Bartolome 1990. Comparison of actual and predicted blue oak age structures. Journal of Range Management 43(1)61-63.

McKenna, J.A. 1936. Black Range Tales, sixty years of life and adventure in the Southwest. The Rio Grande Press, Inc. Glorieta, New Mexico. 300 pp.

Moir, W.H. and J.A. Ludwig 1979. A classification of spruce-fir and mixed-conifer habitat types in Arizona and New Mexico. Ft. Collins, CO. USDA, Forest Service, Rocky Mountain Forest and Range Experiment Station. Research Paper RM-207. 47 pp.

Morgan, P., G.H. Aplet, J.B. Haufler, H.C. Humphries, M.M. Moore, and W.D. Wilson 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry 2:87-111.

Murray, J.A. 1988. The Gila Wilderness, a hiking guide. University of New Mexico Press, Albuquerque 1988. 243 pp.

Myers, R.L. and P.A. Peroni 1983. Approaches to determining aboriginal fire use and its impact on vegetation. Bulletin of the Ecological Society of America. 64(3)216-217.

New Mexico Bureau of Mines 1965. Bulletin 87: Mineral and water resources of New Mexico. Compiled in cooperation with U.S. Geological Survey, State Engineers of New Mexico, New Mexico Oil Conservation Commission and US Bureau of Mines. 67 pp.

Parker and Parker 1994. Structural variability of mature lodgepole pine stands on gently sloping terrain in Park Basin, Colorado. Canadian Journal of Forest Research 24:2020-2029

Page and Garcia 1993. Gila and Aldo Leopold Wildernesses prescribed natural fire plan. USDA Forest Service, Southwestern Region, Gila National Forest. Silver City, New Mexico. 36 pp.

Pase and Brown 1982. Rocky Mountain (Petran subalpine conifer forest). In Biotic Communities of the American Southwest, United States and Mexico (ed. D.E. Brown). Desert Plants 4:37-39.

Peet, R.K. 1981. Forest vegetation of the Colorado Front Range: composition and dynamics. Vegetatio 45:3-75.

Peet, R.K. 1988. Forests of the Rocky Mountains, In: ed. M.C. Bourbour and W.D. Billings, North American terrestrial vegetation. Cambridge University Press, New York, pp. 62-101.

Pyne, S.J. 1982. Fire in America: a cultural history of wildland and rural fire. Princeton University Press, Princeton, NJ. 654 pp.

Ratte, J.C., D.E. Gaskell, G.P. Eaton, D.L. Peterson 1979. Mineral resources of the Gila primitive areas and wilderness, New Mexico. US Geological Survey bulletin 1451. United States Government Printing Office, Washington. 122 pp.

Rixon, T.F. 1905. Forest conditions in the Gila River Forest Reserve, New Mexico. Professional Paper No. 39, Series H, Forestry, 13. Washington: Government Printing Office. 111 pp.

Romme, W. 1980. Fire history terminology: report of the ad hoc committee. In Proceedings of the Fire History Workshop, October 20-24, 1980, Tucson, Arizona (eds. M.A. Stokes and J.H. Dieterich). USDA Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report RM-81:135-137.

Russell, P. 1992. Gila Cliff Dwellings National Monument, an administrative history. Southwest Cultural Resources Center Professional Papers No. 46. USDI National Park Service, Sante Fe, New Mexico. 180 pp.

Savage M. and T.W. Swetnam 1990. Early 19th century fire decline following sheep pasturing in a Navajo ponderosa pine forest. Ecology 71:2374-2378.

Silver City Enterprise 1900. July 13, 1900. Silver City, NM. pp. 1-2.

Silver City Independent 1904A. May 31, 1904. Silver City, NM. pp. 1 and 3.

Silver City Independent 1904B. June 28, 1904. Silver City, NM. pp. 1.

Silver City Press 1938. Progress edition. January 4, 1938. Silver City, NM. 8 pp.

Silver City Press 1974. Fifty year anniversary Wilderness edition, 1924-1974. August 2 1974. Silver City, NM. 14 pp.

Spurr, S.H. and B.V. Barnes 1980. Forest Ecology. John Wiley and Sons, New York. 687 pp.

Stokes, M.A. and T.L. Smiley 1968. An introduction to tree-ring dating. The University of Chicago Press, Chicago, Chicago. 73 pp.

Stomberg, J.C. and D.T. Patten 1991. Dynamics of the spruce-fir forests on the Pinaleno Mountains, Graham Co., Arizona. The Southwestern Naturalist 36:37-48.

Swetnam, T.W. 1983. Fire history of the Gila Wilderness, New Mexico. M.S. thesis, The University of Arizona, Tucson, AZ. 140 pp.

Swetnam, T.W. 1990. Fire history and climate in the Southwestern United States. In Effects of fire management of Southwestern Natural Resources, Proceedings of the Symposium, November 15-17, 1988, Tucson, AZ (ed. J.S. Krammes). USDA Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report RM-191:6-17.

Swetnam, T.W. and J.H. Dieterich 1985. Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. In: Proceedings-symposium and workshop on wilderness fire, Missoula Montana, November 15-18, 1983, Lotan et *al.*, USDA Forest Service, Intermountain Forest Experiment Station, General Technical Report INT-182:390-397.

Swetnam, T.W., M.A. Thompson, E.K. Sutherland 1985. Using dendrochronology to measure radial growth of defoliated trees. USDA Forest Service Agricultural Handbook 639.

Swetnam, T.W. and J. Betancourt, 1992. Fire-southern oscillation relations in the Southwestern United States. Science 249:1010-1020.

Swetnam, T.W. and C.H. Baisan 1996. Historical fire regime patterns in the Southwestern United States since AD 1700. In: Fire effects on Southwestern Forests: Proceedings of the 2nd La Mesa Fire Symposium, March 29-31, 1994. Los Alamos, New Mexico. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. General Technical Report RM-GTR-286:11-32.

Swetnam, T.W. and C.H. Baisan 1997. Fire histories of montane forest in the Madrean Borderlands. In: Effects of fire on Madrean province ecosystems. USDA Forest Service General Technical Report RM-GTR-289:15-36.

Touchan, R.T., C.D. Allen and T.W. Swetnam 1996. Fire history and climatic patterns in ponderosa pine and mixed-conifer forests of the Jemez Mountains, northern New Mexico. In: Fire effects on Southwestern Forests: Proceedings of the 2nd La Mesa Fire Symposium, March 29-31, 1994. Los Alamos, New Mexico. USDA Forest Service, General Technical Report RM-GTR-286:33-46.

USDA Forest Service 1951. Agreement with the New Mexico game and Fish Commission, State of New Mexico, June 28, 1951. Folder 2600, Monument Files, Gila Cliff Dwellings National Monument.

USDA Forest Service 1994. Sustaining our aspen heritage into the twentieth century. USDA Forest Service Southwestern Region, Albuquerque, New Mexico and Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

7 pp.

USDI and USDA 1995. Federal wildland fire management—policy and program review. Final report December 18, 1995. National Interagency Fire Center, Boise, Idaho.

USGS 1965. Mineral and water resources of New Mexico, US Geological Survey Bulletin 87. State Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, Soccorro, New Mexico.

Veblen, T.T., K.S. Hadley and M.S. Reid 1991. Disturbance and stand development of a Colorado subalpine forest. Journal of Biogeography 18:707-716.

Veblen, T.T. 1992. On regeneration and recognition of compositional equilibrium. Pages 153-157 in: D.C. Glenn, Literature cited R.K. Peet, T.T. Veblen, eds., Plant Succession Theory and Prediction, Chapman and Hall Press, 187 pp.

Weaver, 1951. Fire as an ecological factor in the southwestern ponderosa pine forest. Journal of Forestry 49:93-98.

Woodrow, H. 1943. History of McKenna Park District, Gila National Forest. File No. 245 Gila Cliff Dwellings Library. Gila Hotsprings, New Mexico. 26 pp.

Wright, H.A. and A.W. Bailey 1982. Fire Ecology: United States and Canada. John Wiley and Sons, New York. 501 pp.