FINAL REPORT TO BOULDER COUNTY OPEN SPACE

THE HISTORIC RANGE OF VARIABILITY OF FIRE IN THE MONTANE ZONE OF BOULDER COUNTY OPEN SPACE: PAST FIRE TYPES AND FIRE EFFECTS

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ABSTRACT

Most information regarding disturbance history and stand development of ponderosa pine forests has come from the southwestern United States. The results and interpretation of studies in southwestern ponderosa pine forests have been synthesized into a general model of fire suppression and ecological change known as the "Southwestern Ponderosa Pine Model" (SPPM). However, recently the applicability of the SPPM has been questioned for some ponderosa pine ecosystems. Although previous studies in Colorado recognize the importance of stand-replacing fires in the montane zone, some studies suggest that prior to fire suppression in the early 1900s most of the montane zone was less dense with more openings and had fewer stands mixed with Douglas fir. These studies acknowledge that their study areas do not fit the Southwestern Ponderosa Pine Model (SPPM); however, they also infer that most of the ponderosa pine zone in the Colorado Front Range may be currently outside of the historic range of variability of fire and stand structure. My study objective was to examine the effects of fire occurrence in montane habitat types in Boulder County and explore generalizations that can be made about the natural fire regime in different habitat types. Fire history and stand structure were examined at Heil Ranch and at Caribou Ranch on Boulder County Open Space land. Two previously sampled sites on City of Boulder Open Space land are included for a more broad comparison of fire type and fire effects in different site conditions of the lower and upper montane zone. The fire history and age structure data suggest that few, if any sites, beyond areas adjacent to grasslands and low elevation sites historically supported a high frequency-low severity fire regime in Boulder County. Sites only slightly higher in elevation show a dramatic decrease in the historic fire frequency compared to the lowest elevation montane-grassland sites. For the lowest elevation sites of ponderosa pine at the plains-grassland ecotone, data on fire history and stand structure are consistent with the SPPM and strongly support current management prescriptions. However, for upper montane sites and lower elevation north-facing slopes the reduction of fire frequency during the 20^{th} century represents a much less extreme departure from the pre-1900 pattern. These Open Space sites will help to determine what environmental factors allow for a high frequency-low severity fire regime throughout the entire elevational range of ponderosa pine in the northern Front Range.

INTRODUCTION

The development and application of ecosystem-based management is a major paradigm shift in the study and management of native forests in the western United States (Pickett et al. 1992, Christensen et al. 1996). A key component of this new scientific-management paradigm is the recognition of past natural and human-caused variability in disturbance processes and forest conditions, or more succinctly "Historic Range of Variability" (HRV; Landres et al. 1999, Moore et al. 1999, Stephenson 1999, Swetnam et al. 1999). Knowledge of HRV is used to inform management decisions and to consider the possible consequences of managing ecosystems outside of the range of variability under which their current structures have developed (Pickett et al. 1992, Holling and Meffe 1996, Landres et al. 1999). Understanding the interactions of humans with natural environmental variation in determining the current and future conditions of ecosystems is a primary goal of research that supports ecosystem management.

As applied to the management of forested ecosystems in the western U.S., the ecosystem-based management paradigm emphasizes knowledge of the range of ecosystem conditions prior to and following significant changes brought on by intensive Euro-American settlement in the latter half of the 19th century (Kaufmann et al. 1994, Morgan et al. 1994, Swetnam et al. 1999). Managing for the ecological integrity of forested ecosystems must be based on knowledge of key processes that structure and drive ecosystem variation (Holling and Meffe 1996). Understanding the spatial extent and temporal changes of climatically-sensitive disturbances such as fire as ecological mechanisms that have affected forest composition and structure is essential for managing natural areas (e.g. Moore et al. 1999, Stephenson 1999). However, in most ecosystems we lack detailed studies on the behavior and effects of ecological mechanisms such as fire. Knowledge of the disturbance patterns that shape ecosystem structure is fundamental to determine whether contemporary disturbance regimes are within the bounds of the historic range of variability (Landres et al. 1999).

Most information regarding disturbance history and stand development of ponderosa pine forests has come from the southwestern United States. The results and interpretation of studies in southwestern ponderosa pine forests have been synthesized into a general model of fire suppression and ecological change known as the "Southwestern Ponderosa Pine Model" (SPPM; Covington and Moore 1994). The SPPM is a "fire regime-stand development" model, which is implicitly used in much of the management of ponderosa pine forests across the western U.S. According to the SPPM, frequent non-lethal, surface fires formerly maintained open, park-like stands of ponderosa pine, and the past century of fire exclusion has resulted in much denser ponderosa pine stands along with the well known changes in hazard of crown fires and forest health (Covington and Moore 1994).

The SPPM is well supported by data from many ponderosa pine ecosystems from Arizona to Oregon. However, recently the applicability of the SPPM has been questioned for some ponderosa pine ecosystems. For example, Shinneman and Baker (1997) believe that the high fire frequencies assumed in the SPPM prior to the 20th century do not apply to the ponderosa pine forests of the Black Hills National Forest and to many other areas. Although their study certainly did not quantitatively resolve the question of how extensive past stand structural types or past fire regime types were in the Black Hills ponderosa pine forests, Shinneman and Baker (1997) did draw attention to some critical questions about the management of ponderosa pine forests. For the northern Colorado Front Range these questions are:

-In what montane habitats does the SPPM apply?

-Which habitat types that today are characterized by ponderosa pine-montane forest were formerly subject to primarily surface fires, primarily stand-replacing fires, or a mixture of both?

The main objective of this study is to address the first question: To what montane ponderosa pine habitats does the SPPM apply in Boulder County? It may apply to the lowest elevational zone at the grassland-montane ecotone, but how well does it apply to higher elevation stands of ponderosa pine? This question is addressed in stands ranging from open park-like stands dominated by pure ponderosa pine to mixed conifer stands often dominated by ponderosa pine and Douglas fir.

COMPARISON OF FIRE HISTORY STUDIES IN THE FRONT RANGE

Previous work on fire history in ponderosa pine forests in the northern Colorado Front Range describes changes in fire frequency over the past several hundred years in relation to human activities and climatic variability (Veblen et al. 1996, 2000). The lowest elevation ponderosa pine stands were historically characterized by high fire frequencies (e.g. often 8-10 year return intervals to the same small stand or tree) that maintained an open park-like forest structure prior to the early 1900s. However, in higher elevation ponderosa pine forests, much lower fire frequencies (e.g. often > 60 years) have been documented by fire-scar analysis (Veblen et al. 2000). Historical photographs and age structure data document that many ponderosa pine stands were dense and had cohort age structures indicating that they had originated after stand-replacing fires (Veblen and Lorenz 1986, 1991). These patterns are supported by this study and studies in other Front Range ponderosa pine forests from Rocky Mountain National Park south to Pike National Forest (Rowdabaugh 1978, Goldblum and Veblen 1992, Brown et al. 1999, Donnegan 1999, Ehle 2000, Kaufmann et al. 2000).

In Colorado, there is documentation that prior to 1900 many ponderosa pine ecosystems, especially those of the upper montane zone (Marr 1961), were characterized by dense stands and had at least some incidence of stand-replacing fires (Peet 1981, Veblen and Lorenz 1986, 1991, Hadley 1994, Alington 1998, Mast et al. 1998, Ehle 2000, Kaufmann et al. 2000, 2001, Huckaby et al. 2001). On the other hand, some studies suggest that prior to fire exclusion much of the montane ponderosa pine zone was less dense with more openings and had fewer stands mixed with Douglas fir (Kaufmann et al. 2000, 2001, Huckaby et al. 2001). Although most of the studies document that not all ponderosa pine forests in Colorado fit the SPPM, they do not allow us to set the spatial or habitat limits of the forests that do or do not fit the model. For that objective, we need site-specific tree age structure studies in combination with documented fire history at each site. Such studies should make it possible to generalize the habitat types (using elevation and other topographic variables) for which a particular fire regime-stand development model applies.

RESEARCH OBJECTIVE AND QUESTIONS

The objective of this study is to examine the effects of fire occurrence in montane habitat types in Boulder County and explore generalizations that can be made about natural fire regimes in different habitat types.

The specific research questions are:

1. How do fire regimes (e.g. high frequency-low severity fires vs. low frequency-high severity fires) relate to topographic position and elevation?

2. What generalizations can be made about fire regimes, stand structures and habitat type?

3. In what habitats does the Southwestern Ponderosa Pine Model (SPPM) apply?

STUDY AREA

The purpose of this study is to characterize stand structures and fire regimes in the northern Colorado Front Range along the environmental gradient from the lower ecotone to the upper limits of the ponderosa pine distribution. Montane forests extend from approximately 1830 to 2750 m (Marr 1961, Peet 1997). Vegetation of the montane zone varies from open park-like stands of ponderosa pine (*Pinus ponderosa*) at the forest-grassland ecotone to denser stands mixed with Douglas fir (*Pseudotsuga menziesii*) in more mesic sites and north-facing slopes. The sampling areas for this study are located on Boulder County Open Space in the lower montane zone at Heil Ranch and in the upper montane zone at Caribou Ranch (Fig. 1). Separate contiguous areas were sampled in each study site to allow for an extensive analysis of fire history and stand structure across each study site.

Heil Ranch is in the lower montane zone and the elevation of the sampling area ranges from ~1850-2000 m (6080-6600 ft) (Table 1). Fire history in three separate areas of Heil Ranch will be compared to investigate years of local and more widespread fire years in the area. For instance, fire history and stand structure were sampled in two contiguous areas in the drainage of the caretaker's house northwest to the edge of the private ranch. The sampling area ranges from open meadows to dense pure ponderosa pine forests; however, the majority of sampling was done in dense forested areas (Table 2). Fire history was previously sampled along the trail loop in the northern part of Heil Ranch (Veblen et al. 1996; site 32). Due to extensive thinning mitigation in the area that was previously sampled for fire history by Veblen and colleagues (1996), sampling of age structure was not possible in the same area. However, the fire history data will be compared with the more recent sampling of fire history and stand structure in two other contiguous areas of Heil Ranch to examine local and more widespread fire events. Additional sites northwest and southwest of Heil Ranch Open Space have also been sampled and will provide more extensive information about widespread fire years throughout the lower montane area of Lefthand Canyon and the South St Vrain Canyon (Sherriff and Veblen in progress, Veblen et al. 1996).

The upper montane vegetation at Caribou Ranch ranges from open meadows to dense mixed conifer stands composed of ponderosa pine, lodgepole pine, limber pine, aspen and a few Douglas fir (Table 2). The Boulder County Management Plan for Caribou Ranch provides a detailed description of the area; this description specifically pertains to the area that was sampled for fire history and stand structure. The sampling elevation ranged from ~2600-2630 m (8600-8660 ft) in elevation (Table 1). Fire history was broadly sampled and age structure was sampled in separate contiguous locations south of Delonde Creek and north of Sherwood Creek. Heavy landuse history (e.g. mining and logging) made it difficult to extend the age structure sampling beyond the designated areas. For instance, areas with abundant logging and mining make it unfeasible to interpret the stand structure history in relation to fire history in contrast to the changes in landuse history.

The preliminary fire history data from Brown and Carpenter (2001) was used as a guide for this more intensive collection of fire history and forest age structure. Although Brown and Carpenter (2001) sampled for age structure, the age structure sampling does not provide enough detail to resolve the historical effects of fire types (e.g. stand-replacing or surface fires) on forest stand regeneration. For example, the report has a low sample number of tree ages with an unspecified age-to-coring-height error, and no information on the effects of logging for the age structure interpretations. A more intensive sampling of age structure and record of disturbances such as logging were done in this study to clarify the initial interpretations made in the report. The age structure and fire history sampling of this study was done in areas adjacent to those previously sampled by Brown and Carpenter (2001) for non-overlapping studies.

The Boulder County Open Space sites will eventually be analyzed with a total of approximately 20 sites identified throughout Boulder County (City of Boulder Open Space, Boulder County Open Space), the Arapaho-Roosevelt National Forest and in Rocky Mountain National Park. Two additional sites from the City of Boulder Open Space and Mountain Parks land sampled in 2001 are included in the discussion section for a more broad comparison of lower to upper montane habitats throughout Boulder County (Fig. 1). The City of Boulder Open Space sites are at the grassland-forest ecotone at the base of Eldorado Springs (~1900 m) and at slightly higher elevation in Long Canyon (~2100m) on Flagstaff Mountain (Table 1). These two sites in the lower montane zone range from open park-like stands at the forest-grassland ecotone near Eldorado Springs to denser stands composed of ponderosa pine-Douglas fir stands at Long Canyon (Table 2). The lowest elevation study area near Eldorado Canyon is on a north-south ridge on the northern side of Eldorado Springs. Long Canyon was sampled for age structure and fire history for a slightly higher elevation lower montane site and is dominated by a dense ponderosa pine-Douglas fir stand. Fire history was previously sampled in these two areas by Veblen and colleagues (1996; Site 15-Eldorado Springs, Site 11-Long Canyon).

Precise historical records of grazing were unavailable, although within the last few decades the intensity of grazing in the Boulder area has been reduced (e.g. changes in landuse; conversion to Open Space land). Logging has occurred at all sites, though the small number of stumps recorded in most of the sampling areas indicates the activity was low (Table 2). However, the Long Canyon site has been heavily affected by human disturbances such as logging and recent thinning, which makes the interpretation of the historical effects of fire on stand structure difficult to distinguish from more recent human disturbances. Evidence of mining, logging and extensive landuse (e.g. EuroAmerican settlement to present) was widespread at Caribou Ranch; however, sampling areas were chosen within minimal human disturbance. Cattle grazing and minor logging disturbances appear to have been the main human-induced disturbances in the areas sampled at Heil Ranch.

STAND DEVELOPMENT AND DISTURBANCE HISTORY METHODS

Meso-scale Sampling of Fire History and Age Structure

Non-destructive partial cross-sections from live and dead trees with fire scars were collected at both Heil Ranch and Caribou Ranch (Arno and Sneck 1977, McBride 1983) in combination with the meso-scale tree age structure. Depending on availability, I sampled approximately 20 fire-scarred trees in each study area (Table 1). For example, in dense stands that originated after a stand-replacing fire there are few fire-scarred trees to sample (e.g. Long Canyon and Heil Ranch), but a few scars must be sampled to more precisely determine the age of the post-fire cohort as determined from tree ages.

Over these relatively large areas, I sampled age structure with the point-quarter method (Barbour et al. 1987) and size structure along belt transects (10x200m transects). All trees > 1.4 m in height were included in the sample of size structure, seedlings and saplings were counted, and trees > 4 cm in diameter were cored. Along each transect, the closest tree every 20 meters in the northwest corner was cored (approximately ~132 trees for age structure) and older cohort trees were subjectively chosen for age sampling. Tree-rings were crossdated and counted to determine approximate tree germination dates. To estimate the ages of trees too small to core (< 4 cm in diameter) and to estimate the number of rings missed due to coring height (approximately 20 cm above the root-shoot boundary), existing data was used for seedling ages from nearby areas (Veblen and Lorenz 1986, Mast et al. 1998). An age estimate of 5 years was used for ponderosa pine following values reported for Boulder County at 40 cm above the root-shoot boundary (range 5-10 years) by Mast et al. (1998). Five years to coring height was also used for other pine species such as limber and lodgepole pines. Although Mast et al. (1998) did not report Douglas fir and Rocky Mountain juniper values for Boulder County, the authors found a slightly longer and similar age-to-coring height relationships compared to ponderosa pine from Rocky Mountain National Park measurements. Based on this, an age estimate of 8 years was used for the age-to-coring height for Douglas fir.

Fine-scale Sampling of Stand Structure and Disturbance History

At both Heil Ranch and Caribou Ranch, random points within meso-scale sampling areas were located and a complete census of age structure and disturbance history were collected to reconstruct spatial stand structure and disturbance events at various times in the past (e.g. Henry and Swan 1974, Fule et al. 1997). The purpose of the fine-scale sampling is to verify the tentative models of fire regimes and stand development for each study area where logging or other human-induced disturbances have not occurred. For example, at some sites fire-scarred trees may have been removed by logging so that the record of fire history is incomplete or ambiguous. This ambiguity is removed by conducting the fine-scale sampling at unlogged sites. Prior work has shown that due to the slow decay of cut stumps it is feasible to detect logging even as long ago as the late 1800s (Veblen and Lorenz 1986, 1991). Plots varied in size to assure that around 80 trees were included at each site and all trees were mapped on a 1 by 1 meter grid. This involved determining the ages of close to 100% of the living trees as well as ages and dates of tree death for standing dead trees and fallen trees. Ages and dates of the death of dead material were determined by crossdating them against living trees (e.g. Villalba and Veblen 1998).

RESULTS

Meso-scale Sampling of Fire History and Age structure

Heil Ranch

Fire History

A total of 16 fire-scar samples were broadly sampled from live and dead trees (primarily stumps) in which 14 samples were accurately dated with a total of 34 fire scars and 13 fire years. All samples were statistically crossdated using the COFECHA program using a master ponderosa pine tree-ring chronology (Veblen et al. 2000) representing regional climate conditions. Although fire-scar samples were taken in separate areas of the drainage, the fire history trends were the same for all areas and are shown as a composite fire history for the entire study area (Fig. 2). The fire chronology is 406 years with the earliest fire date in 1686 and the most recent in the early 1900s (either 1900 or 1911). Due to the difficulty of accurately dating fire-scar samples, some dates are bracketed (e.g. 1760-1777) or the exact date is unknown (e.g. 1900 or 1911 fire date). Years with at least three fire-scarred trees (or stumps) are 1686, 1733-34, 1786, 1814 and 1840 most likely indicating more widespread fire years. For instance, fire years 1686, 1786, 1814 and 1840 scarred at least 70% of the recorder trees (recorder trees are previously fire-scarred trees that have an exposed scar and will subsequently record fires that occur at the site). Other fire years scarring only one or two trees are 1714, 1760-1777, 1803, 1847, 1866 or 1869, 1871-72, 1889, and 1900 (or 1911). These fire years may represent more local low severity fires scarring only one or two trees; however, severe fires may not leave many scars and may devastate remnant cohort trees as well (e.g. the age structure data along with the fire-scar data is necessary for interpreting historical fire severity). There are numerous scarlets on fire-scar wedges and tree core samples that suggest fire occurrence around 1947-48; however the precise date and supporting evidence is uncertain. There is also more recent evidence of a low severity fire of limited extent in the late 1980s to early 1990s from charred bark on many trees and injuries on many tree core samples in one of the sampling areas. These two latter dates are not shown in the fire history diagrams (Figs. 2-3) because of the uncertainty.

The fire-scar record shows a moderately high fire frequency from the 1700s through the late 1800s with a major decline in fire occurrence during the 1900s (Fig. 2). There is also a decline in fire-scar sample number during the 20th century and the decrease in sample depth needs to be considered when interpreting the decline in fire frequency. There were few live trees with fire scars and most of the fire-scar samples were taken from old decaying stumps. Nevertheless, the overall fire history trend shows a major decrease in fire frequency in the 20th century from the prior two centuries (Fig. 2).

Fire history from site 32 in the northern part of Heil Ranch also shows a decline in fire frequency during the 20th century (Fig. 4). Although only seven samples were taken from the northern area (site 32), the fire frequency trend shows a clear pattern of a moderately high fire frequency from the 1700s with a decline in the 20th century (analogous to the other sampling area). Fire dates with at least two fire-scarred trees in the northern area are 1739, 1786, 1852, and 1873. The 1786 fire date is also a major fire year in the other sampling area at Heil Ranch (Fig. 2) as well as a widespread fire year in the montane zone across the northern Front Range (Veblen et al 1996).

Age Structure

Tree establishment dates were determined from 133 tree core samples across all sampling areas. 144 tree core samples were taken in the field but 11 cores were not used because of decay, injuries or core samples were too far from the pith. Tree ages are from the meso-scale sampling (fine-scale plot age structure will be discussed below). All of the tree ages determined were ponderosa pine given that the cover type composition was pure ponderosa pine (Table 2). Sixty-three percent of the core samples had the pith date and all other samples analyzed were estimated within 10 years of the pith using Duncan's method (Duncan 1989). Tree ages were counted and visually crossdated and then adjusted using five years as the age-at-coring height (~ 20cm above root-shoot boundary).

Age structures were similar across all sampling areas at Heil Ranch. In order to examine trends over time, the age structures for all areas were combined for a larger sample size. Most of the tree establishment dates between 1880 to 1930 (Fig. 3). The 1880-1930 period of ponderosa pine establishment follows a period of high fire frequency with fire dates in the late 1860s, 1871-72, 1889 and in the early 1900s (either 1900 or 1911) with no major fire events after the early 1900s (perhaps 1947-48). There is a slight trend of continuous recruitment through the 20^{th} century, but few trees established in the latter 20^{th} century (5 trees after 1950). There are small tree recruitment pulses following fire events in 1714, 1760-1777, 1796, and 1840 and 1847 (Fig. 3); however it is difficult to decipher the size of recruitment pulses through time because of overburning of subsequent fires. For instance, 1786 was a widespread fire year but there are few remnant post-fire cohort dates most likely due to overburning of fires in the 1800s.

Caribou Ranch

Fire History

Twenty-four fire-scarred trees and stumps were sampled at Caribou Ranch in which 20 samples were accurately statistically crossdated. The 20 fire-scar samples yielded 29 fire scars and 11 fire years. The fire history chronology is 453 years with the earliest date ~1601 and the most recent date in 1925 (Fig. 5). Many of the fire dates were difficult to decipher and bracketed dates were necessary. Further investigation of exact fire dates may be useful. Fire years with at least three fire-scarred trees are 1709-10, 1850, 1859-60 and 1910-12. At least 60% of the recorder trees were fire scarred in ~1601 (only 1 tree), 1709-1710, 1850 and 1859-60 (Fig. 6). A few of these dates, 1709, 1859-60 and 1871, are also widespread fire years across the montane zone in the northern Front Range (Veblen et al. 1996). Other fire years recorded at Caribou Ranch on one or two trees are ~1601, 1658-59, 1661, ~1871, ~1896, 1904, and 1925.

The fire-scar record indicates a moderately high fire frequency during the late 1800s through the early 1900s during the EuroAmerican settlement period (Fig. 5). The last fire recorded was in 1925 with no other fire years in the record to present. Prior to the late 1800s there are few fires during most of the 1700s through the early 1800s. However, there are three fire dates during the early to mid-1600s.

Although there is a clear decline in fire occurrence during the late 1900s, it is not clear that the decline in fire frequency is outside of the range of variability because of the similar, and even longer, gap in fire occurrence from the early 1700s through the mid-1800s (Figs. 5-6). The same trend is shown in Carpenter and Brown (2001) with no fires occurring between 1706 and 1834. The absence of fire occurrence from the late 1700s through the early 1800s is illustrated in other fire history studies in Colorado as well (e.g. Donnegan 1999, Veblen et al. 2000). These studies indicate that long-term variability in fire occurrence (e.g. periods of high fire frequency versus periods of low fire frequency) is associated with decadal and year to year climatic variability.

Age Structure

The composition of the sampled stands at Caribou Ranch range from pure ponderosa pine to mixed conifer with ponderosa pine, lodgepole pine, limber pine, aspen and Douglas fir. The stands are primarily composed of ponderosa pine with 73% composition, lodgepole pine 19%, limber pine 5%, aspen 2% and <1% of Douglas fir. A total of 146 trees were sampled for age and 125 were used for the final analysis of age structure. Tree ages are from the meso-scale sampling and 11 tree cores taken subjectively from old cohort trees (all old cohort trees are ponderosa pine). Ninety-three tree ages are from ponderosa pine, 14 tree ages are from lodgepole pine, and five tree ages are from limber pine shown in Figure 6. Two tree ages from aspen trees are not shown (the two aspen establishment dates are 1900 and 1953). Sixty-two percent of the core samples had the pith date and all other samples analyzed were estimated to be within 10 years of the pith except for five tree ages from the 1700s (10-20 years estimated from pith). Tree ages were counted and visually crossdated and then adjusted using five years as the age-at-coring height (~ 20cm above root-shoot boundary) analogous to the Heil Ranch samples. There were no distinct age structure trends segregating sample areas, thus all areas were compiled together for a more robust examination through time.

The majority of the trees in the sampling areas of Caribou Ranch date from 1870 to the early 1900s (Fig. 6). This pulse of establishment follows three fire years 1850, 1859-60 and ~1871. Other dates in the late 1800s to early 1900s may have also contributed to the continuous recruitment of ponderosa pine and lodgepole, however the number trees establishing in the 20th century is small (15 ponderosa, 6 lodgepole). There are earlier tree ages from the 1600s through the early 1800s, but it is unclear if these are pulses of establishment dating from fire occurrence because of the low sample number. For instance, there are slight peaks in establishment following the ~1601 and 1709-10 fires, but should be interpreted cautiously (Fig. 6). Four remnant ponderosa pine trees from the 1500s are not shown in Figure 6, but the dates of establishment are approximately 1517 (two trees), 1551 and 1586.

Spatial Analysis of Disturbance History and Stand Structure

At Heil Ranch and Caribou Ranch, random points within meso-scale sampling areas were located for fine-scale plot sampling of age structure and disturbance history to reconstruct spatial stand structure and disturbance events at various times in the past (e.g. Henry and Swan 1974, Fule et al. 1997). This allowed for mapping of stand structures and ages associated with fire occurrence to provide further indication of the importance of different fire types (surface fires and stand-replacing fires) on vegetation. Plots varied in size to assure that around 80 trees are included at each site and all trees were mapped on a 1 by 1 meter grid. This involved determining the ages of close to 100% of the living trees as well as ages and dates of tree death for standing dead trees and fallen trees. The same procedures described above for dating the meso-scale tree establishment dates were used for the plot cores.

Heil Ranch

Ninety tree ages were sampled in a 20 by 60 meter plot in which 78 tree ages were adequately crossdated for analysis. No fire-scarred trees were found for sampling within the plot, although fire-scar samples were taken from surrounding areas. The complete age structure in the plot indicates the majority of trees established from 1880 to 1930 (Fig. 7). Analogous to the broader sampling of age structure (Fig. 3), this period of tree establishment follows fire years in the late 1800s (1871-72, and possibly 1889 and 1900 or 1911). There is a small pulse of establishment from 1840 through 1860 likely following the 1840 fire. There are no trees younger than 1960, and only one tree established in the 1950s (Fig. 7). There are numerous scarlets on fire-scar wedges and tree core samples that suggest fire occurrence around 1947-48 in the location of the plot; however as mentioned previously the precise date and supporting evidence are uncertain. The tree establishment dates from the plot clearly indicate post-fire tree recruitment from the late 1800s rather than recruitment from a decline in fire occurrence during the 20th century.

For the spatial pattern analysis, classifications of establishment cohort time periods (e.g. 1880-1900) were chosen by examining natural breaks in establishment dates. The spatial pattern shows most of the plot dominated by the 1880-1900 cohort (Fig. 8), which likely established following the 1871-1872 fire (and perhaps the later fire ~1889). However, there are few trees dating from the 1880-1900 cohort in the western part of the plot (Fig. 8). Most of the trees in the western part of the plot date from the 1901-1930 cohort. The 1901-1930 cohort likely established from another fire in the late 1800s or early 1900s. This suggests that the early 1900s fire was of lower severity in the eastern part of the plot were the majority of the trees date from 1880-1900 and/or few trees were able to establish because of the high density 1880-1900 cohort in the eastern part of the plot (Fig. 8). The older cohort trees from 1840-1860 are also located in the western part of the plot, suggesting that the fire(s) initiating the 1880-1900 cohort was less severe in the western part of the plot leaving remnant trees. In general, the spatial pattern of cohort ages suggests that fire spread is extremely patchy even at a fine scale.

Caribou Ranch

At Caribou Ranch, 87 trees were cored for a complete age structure in a 20 by 20 meter randomly located plot. Eighty-four tree ages were used for the age structure analysis in which 67 were ponderosa pine and 15 were lodgepole pine trees. Two fires were recorded on three trees in the plot in 1859-60 and ~1896 (sample numbers Carib11, Carib18 and Carib19; Fig. 5), and other fire-scar samples were taken from surrounding areas. There are no establishment dates prior to the 1870s (Fig. 9). The majority of ponderosa pine establishment occurs during the 1890s, which likely established after the ~1896 fire that dates from within the plot. A small number of ponderosa pine continuously established through the 1950s, although the number is low after 1910 (18 trees and 9 saplings; Fig. 9). The lodgepole pine trees established from the 1870s through 1910 and probably established following the ~1871 fire from evidence of nearby fire scars. The lodgepole pine trees are primarily located in the northwest part of the plot suggesting the ~1871 fire may have been more severe in that area.

Classifications of establishment time periods (e.g. 1870-1900) were chosen by examining natural breaks in establishment dates analogous to the method used for the Heil Ranch plot. The density of the stand is very high due to the post-fire cohort of around 1870-1900, which limited the plot size to 20 by 20 meters (Fig. 10). There are three remnant trees from 1620-1650 surrounded by saplings, which indicates a more open forest structure that allowed the establishment of seedlings. The patch of remnant trees also suggests that subsequent fires in the late 1800s were probably of lower severity in that area of the plot; however in other areas of the plot remnant trees may have been killed. The 1870-1900 and 1901-1930 cohorts have overlapping ranges suggesting the ~1896 fire was of moderate to low severity leaving many older trees, and the ponderosa pine age structure probably represents a long period of recruitment from the 1870s through the early 1900s after fire occurrence (Fig. 10). The overall trend in age structure is similar to the meso-scale sampling (Fig. 6), yet the spatial pattern clearly shows some spatial heterogeneity in tree ages and fire severity even within a $20m^2$ area (Fig. 10).

CONCLUSION

The overall fire history trend at Heil Ranch shows a definite decrease in fire frequency in the 20^{th} century from the prior two centuries (Figs. 2 and 4) suggesting that some areas may be outside of the historical range of variability in terms of fire frequency. Yet, the age structure indicates that stand-replacing fires have been important for establishment, which suggests that the stand structure is not outside of the historical range of variability. In the sampling area at Heil Ranch there are few trees younger than 60 years suggesting that these dense stands have not been substantially altered due to the onset of fire suppression in the early 1900s, more likely these dense stands are a result of partially stand-replacing fires in the late 1800s. For instance, at a fine scale it is clear that the dense stands sampled for age structure represents a post-fire cohort from fires in the late 1800s-early 1900s and few to no trees established in the late 1900s to present (Fig. 7). The stand structure indicates that periodic stand-replacing or partially stand-replacing fires have initiated pulses of tree establishment rather than the high fire frequency regime reducing continual recruitment.

This is interesting because there is recent tree encroachment into grassland areas adjacent to these dense stands. Different disturbance mechanisms seem to be important in the dense forested areas versus the grassland areas at Heil Ranch; however, additional research needs to be done on investigating regeneration dynamics in the grassland areas before any conclusive statements can be made contrasting the two habitats. Likewise, other areas of the Open Space property may have a different pattern of recruitment following the decline in fire frequency during the 20th century. Additional field research should be done at Heil Ranch to investigate recent tree encroachment into meadow areas because the main focus of this research was in forested areas of the site.

Similar to Heil Ranch, the majority of the tree establishment dates at Caribou Ranch are during the late 1800s to early 1900s, with a distinct pulse from 1870 to 1900 (Fig. 6). There are earlier potential establishment pulses in the 1600s and also in the 1700s that would need further tree age sampling for a clear interpretation. Brown and Carpenter (2001) did not find distinct cohorts of tree ages following fire occurrence, but the evidence from this study suggests that there are clear cohort ages from the late 1800s suggesting periodic severe widespread fire at Caribou Ranch. For instance, two major fire dates at Caribou Ranch scarring at least 50% of the recorder trees, 1709-10 and 1859-60, match widespread fire years associated with drought conditions in other areas of the montane zone of Boulder County (Veblen et al. 1996, 2000).

The fire frequency at Caribou Ranch is quite variable through time with long periods of no fire occurrence (e.g. late 1700s-early 1800s) and other time periods of high fire frequency (e.g. EuroAmerican settlement period; Fig. 5 and Brown and Carpenter 2001). Given the historical variability of fire occurrence, it is not clear that the absence of fire in the late 1900s is outside of the historical range of variability at Caribou Ranch. Many of the high-density stands that were sampled are post-fire cohorts dating from fires in the late 1800s and early 1900s. However, there is a clear relationship between tree recruitment during the 20th century due to human disturbances such as increased burning, mining, logging and landuse changes. Field observations indicate many of the younger trees are in areas of high human disturbance. For instance, many ponderosa pine trees have established on old mining pits due to the open, coarse soil and the lack of competition with grasses. The fire history record at Caribou Ranch indicates a variable fire regime composed of periods of more frequent fires with low and high severity fires, and periods of low fire frequency with no fire occurrence. Caribou Ranch is at the upper elevations of the montane zone and much of the area has likely been affected by periodic infrequent stand-replacing fires that occur in adjacent subalpine lodgepole and spruce-fir forests, as well as more frequent low severity fires such as 1904 and 1925.

IMPLICATIONS FOR FOREST MANAGEMENT IN BOULDER COUNTY

At the grassland-montane ecotone, the high grass understory would have supported frequent, low severity fires. For instance, a site near Eldorado Springs shows an obvious increase of tree establishment with the onset of active fire suppression during the early 1900s; however the beginning of the increase in tree establishment pre-dates fire suppression efforts in some areas and is likely due to the last major fire in the late 1800s (Fig. 11). The Eldorado Springs site has an historical fire regime of high frequency-low severity fires. The Southwestern Ponderosa Pine Model (SPPM) appears to be applicable at the grassland-montane ecotone near Eldorado Springs. Frequent non-lethal, surface fires formerly maintained open, park-like stands of ponderosa pine, and the past century of fire exclusion has resulted in much denser ponderosa pine stands along with the well known changes in hazard of crown fires and forest health (Covington and Moore 1994). Environmental factors such as topographic position may be inconsequential for determining fire regime type (high frequency-low severity vs. low frequency-high severity) in areas adjacent to grasslands and at low elevation. This pattern of fire reduction followed by a sharp increase in stand density fits well with the SPPM. Current management plans are guided by the recognition that in this habitat (near Eldorado Springs) fire frequency during the past century is outside the historic range of variability, and so is the current stand density.

Heil Ranch also shows a moderately high fire frequency until the early 1900s with a decline in fire occurrence, presumably with the onset of fire suppression efforts and changes in grazing and other landuse (Fig. 3). However, the age structure does not clearly show the onset of tree recruitment following the decline in fire occurrence as the Eldorado Springs site (compare Figs. 3 and 7 with Fig. 11). Both the Eldorado Springs and Heil Ranch sites are in the lower montane zone below ~2000 meters in elevation and on south-southeast facing slopes. These habitat types (low elevation, south-facing slopes) appear to have supported high to moderately high fire frequency regimes. However, the Heil Ranch site shows an historic high frequency but mixed fire severity regime (interpreted with the age structure) composed of both low and high severity fires in contrast to the low severity fire regime of the Eldorado Springs site. The lowest elevation areas adjacent to the grassland ecotone show a substantial change in the fire regime allowing for tree invasion into the grassland; however, many of the montane forests in the northern Front Range show even-aged pulses of establishment indicating a low frequency-high severity or -mixed severity fire regimes (e.g. Heil Ranch and Caribou Ranch; and other sites, Sherriff and Veblen unpublished).

Fire history and age structure data suggest that few, if any sites, beyond areas adjacent to grasslands and at low elevation would support a high frequency-low severity fire regime in the northern Colorado Front Range. Sites only slightly higher in elevation show a dramatic decrease in the historic fire frequency (Fig. 12) compared to the lower elevation montane sites (e.g. Eldorado Springs and Heil Ranch). In the lower montane stand of Long Canyon there is no evidence that frequent surface fires played a detectable role in the history of this stand over the past several hundred years (Fig. 12). Although the effects of fire occurrence on stand structure are unclear in Long Canyon due to recurrent human disturbances increasing stand densities in the 20th century, management efforts to restore this site to an open, park-like woodland would not be consistent with the fire history at this site. The fire history record at Caribou Ranch (in the upper montane zone) indicates a variable fire regime composed of periods of more frequent fires with low and high severity fires, and periods of low fire frequency with no fire occurrence (Fig. 5-6). Given the historical variability of fire occurrence, it is not clear that the absence of fire in the late 1900s is outside of the historical range of variability at Caribou Ranch. Many of the high-density stands that were sampled are post-fire cohorts dating from fires in the late 1800s and early 1900s. Although fire suppression during the present century may have prevented another stand-replacing fire from occurring, this type of fire history and stand structure clearly does not fit the SPPM.

For the lowest elevation sites of ponderosa pine at the plains-grassland ecotone, data on fire history and stand structure are consistent with the SPPM and strongly support current management prescriptions. However, for upper montane sites and lower elevation north-facing slopes the reduction of fire frequency during the 20th century represents a much less extreme departure from the pre-1900 pattern. In context of ecosystem-based management, it is critical that we have a better understanding of the spatial variability of fire regime type (surface, stand-replacing, or mixed) as it has changed over the past several centuries in ponderosa pine forests.

We know that fire regimes have varied significantly over both time and space in the montane zone, but we need to focus on classifying past fire regimes according to habitat type.

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Table 1. Study Area Information

Site Name	Elevation (m)	Area (ha)	Slope Aspect	No. Fire-scar Samples[1]	Total No. Trees Sampled for Age[2]	Sampled Species	Forest Type
Heil Ranch	1850-2000	200	E to SW	21	211	*Pinus ponderosa*	Pure Ponderosa Pine
						Pinus ponderosa	
Caribou Ranch	2600-2630	130	NE to SE	20	160	*Pinus ponderosa*	Pure Ponderosa Pine to Mixed Conifer
					29	*Pinus contorta*	
					5	*Pinus flexilis*	
					2	*Populus tremuloides*	
Eldorado Springs	1900	25	S to SE	37	115	*Pinus ponderosa*	Grassland-Ponderosa Ecotone
					2	*Pseudotsuga menziesii*	
Long Canyon	2100	24	NE	10	112	*Pinus ponderosa*	Ponderosa-Douglas fir
					20	*Pseudotsuga menziesii*	
					2	*Populus tremuloides*	
					2	*Juniperus scopulorum*	

[1] 14 fire-scar samples were taken in the area sampled for age structure and 7 fire-scar samples at Heil Ranch were previously sampled for fire history by Veblen et al 1996 (site 32); Eldorado Springs and Long Canyon previously sampled by Veblen et al 1996 (site 15 and site 11, respectively)

[2] Total number of trees sampled for age includes meso-scale and fine-scale plot sampling and old trees subjectively sampled at Heil Ranch and Caribou Ranch

Table 2. Forest stand information for each study area

Site	Species	Tree Density/ Hectare	Number of Saplings[a]/ Hectare	Number of Logs[b]/ Hectare	Number of Stumps[b]/ Hectare	Number of Snags[b]/ Hectare
Heil Ranch	Ponderosa	626	31	24	3	1
	Douglas fir		1			
	unknown			21	13	
Caribou Ranch	Ponderosa	589	39	14	6	2
	Lodgepole	155	11	4	3	1
	Limber pine	39	14			
	Aspen	18	145	26		
	Douglas fir	2	1			
	unknown			45	15	7
Eldorado Springs	Ponderosa	133	30	17	18	
	Douglas fir	2	1			
	Juniper	1				
Long Canyon	Ponderosa	208	54	28	70[c]	5
	Douglas fir	86	24			
	Juniper	17	6			

[a] Some saplings may be suppressed and more than 20 years old.
[b] Most of the dead material unidentified is believed to be ponderosa pine.
[c] Stumps were primarily from one sector of sampling area at Long Canyon.

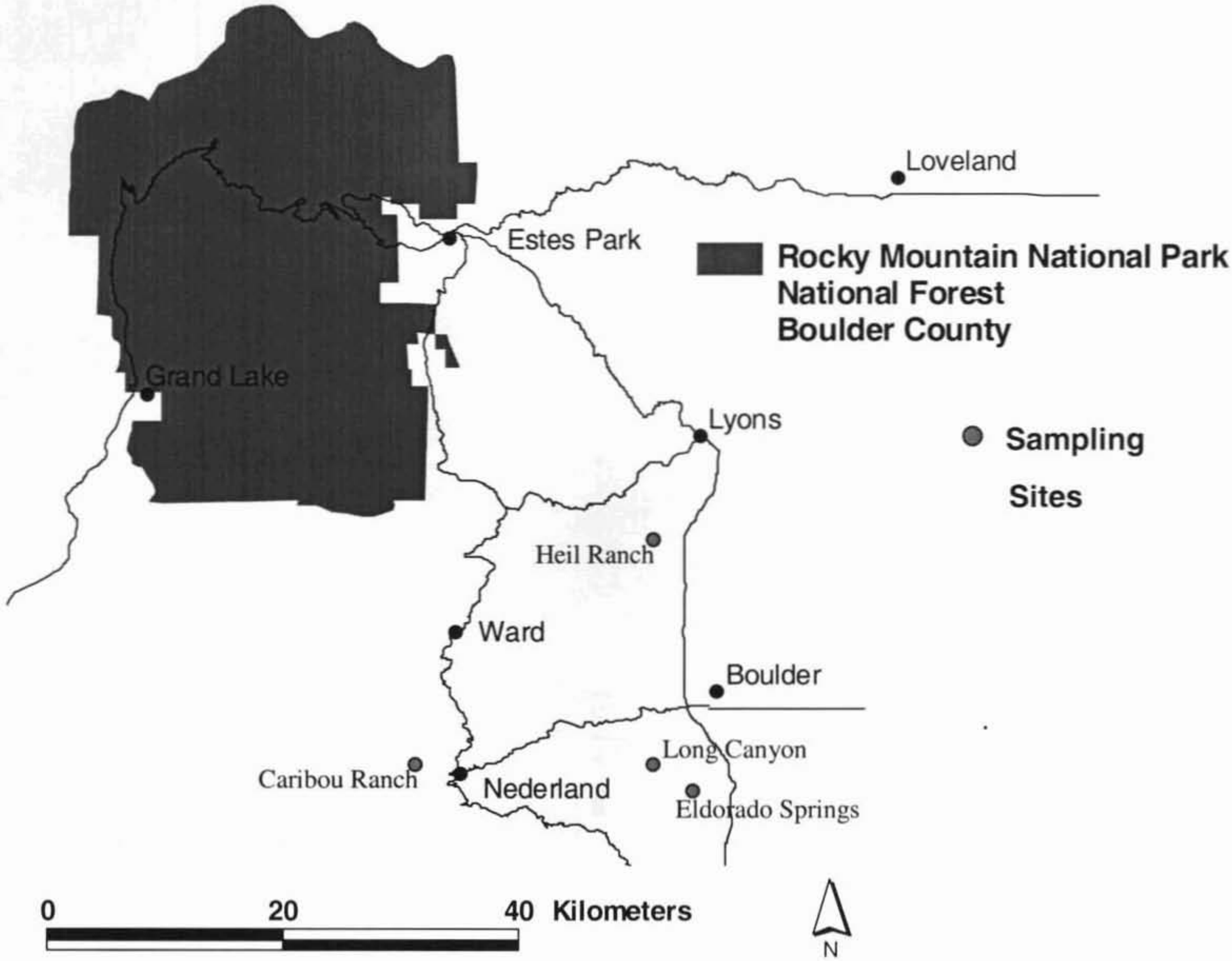
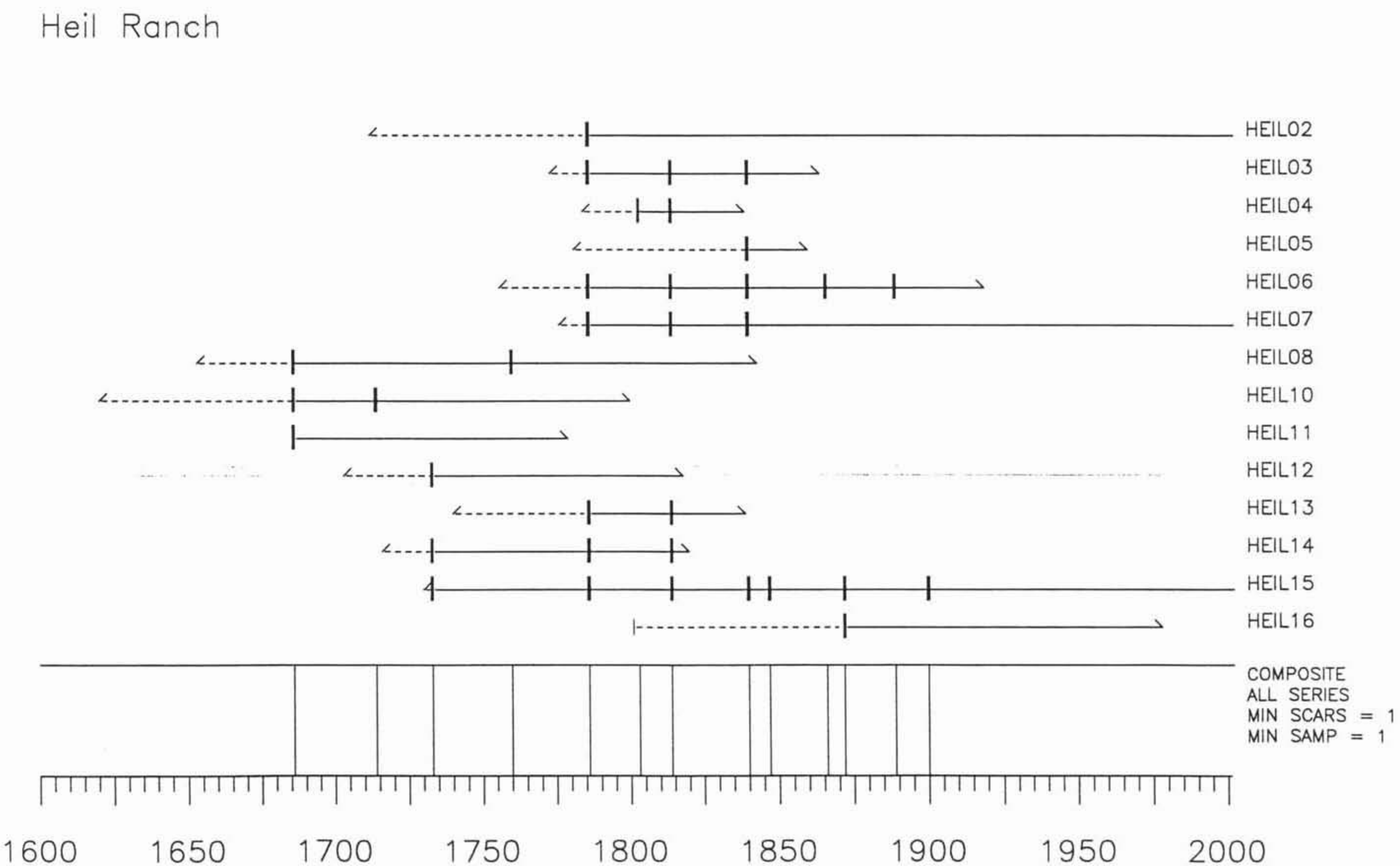


Figure 1. Map of study sites in Boulder County. The dark circles indicate sample sites. Study areas on Boulder County Open Space land are Heil Ranch and Caribou Ranch. Other sampled sites on City of Boulder Mountain Parks and Open Space land discussed in the report are at Eldorado Springs and Long Canyon.

Figure 2. Composite fire-scar record for Heil Ranch indicating fire years. Graphs were created using the FHX2 program. Each horizontal line represents an individual tree. Short vertical lines on each horizontal line indicate fire-scar dates. Dashed lines indicate years prior to the first fire-scar date on each individual sample.


Heil Ranch
HEIL02
HEIL03
HEIL04
HEIL05
HEIL06
HEIL07
HEIL08
HEIL10
HEIL11
HEIL12
HEIL13
HEIL14
HEIL15
HEIL16
COMPOSITE
ALL SERIES
MIN SCARS = 1
MIN SAMP = 1
1600
1650
1700
1750
1800
1850
1900
1950
2000

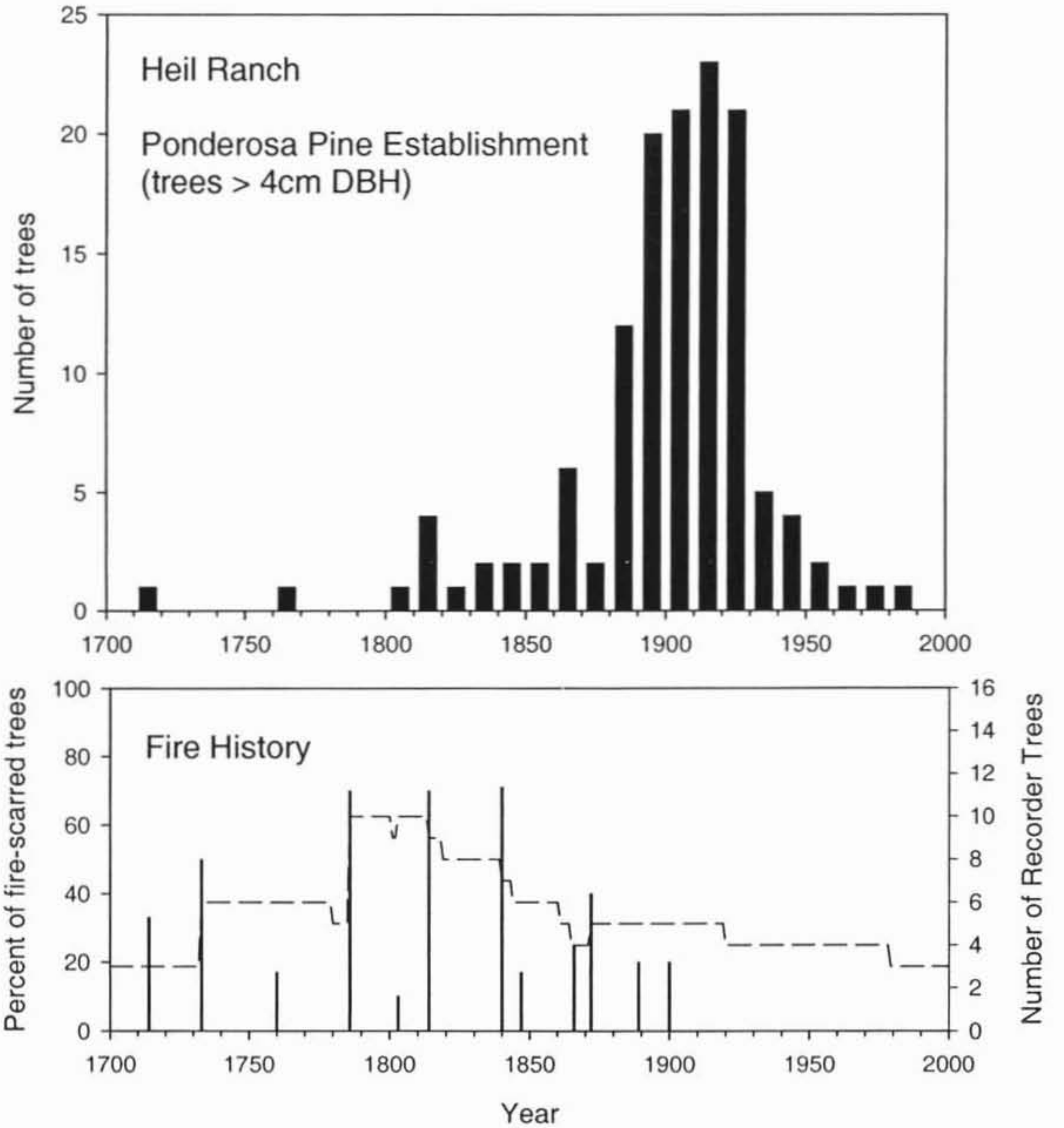


Figure 3. The top graph represents the age structure of live trees (> 4cm DBH) for the Heil Ranch study site. The histogram shows the age structure of ponderosa pine trees. The bottom graph represents the fire history in the same sampling areas. The vertical bars indicate the percentage of trees fire-scarred (left axis) during an individual fire year. The dashed line represents the number of recorder trees (right axis) through time. Recorder trees are previously fire-scarred trees that have an exposed scar and will subsequently record fires that occur at the site.

Figure 4. Composite fire-scar record for Site 32 at Heil Ranch indicating fire years (sampled by Veblen et al 1996). Graphs were created using the FHX2 program. Each horizontal line represents an individual tree. Short vertical lines on each horizontal line indicate fire-scar dates. Dashed lines indicate years prior to the first fire-scar date on each individual sample.

Site 32 (Heil Ranch)

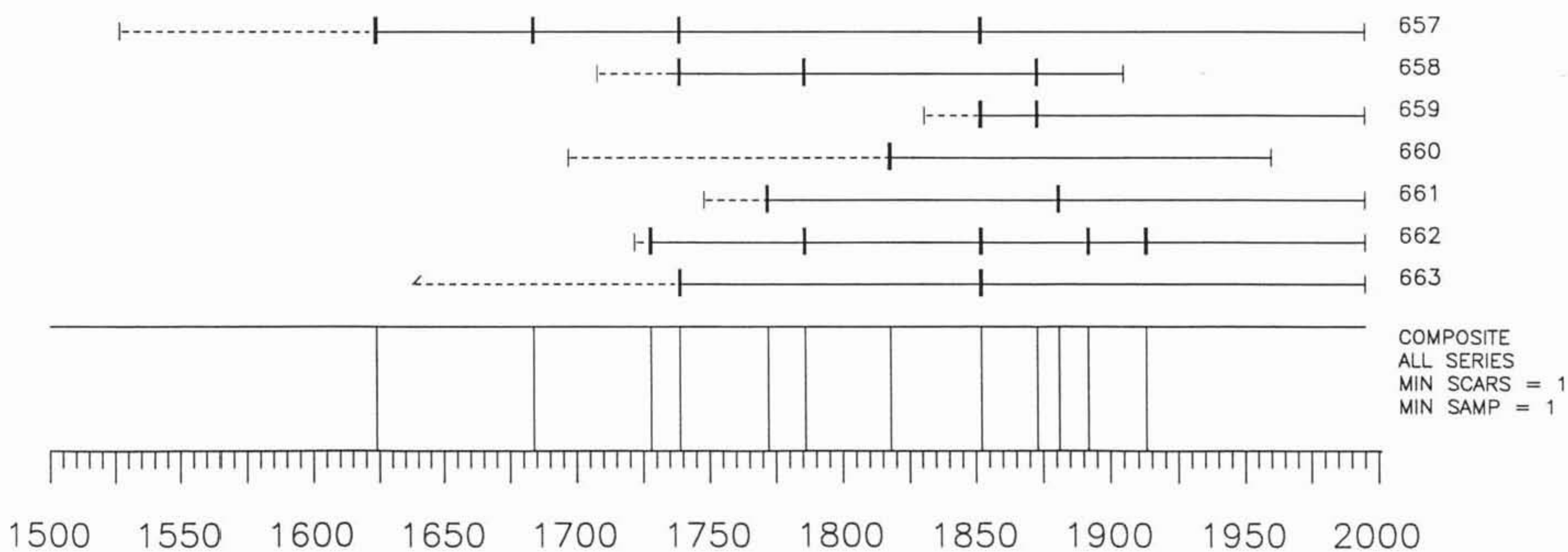
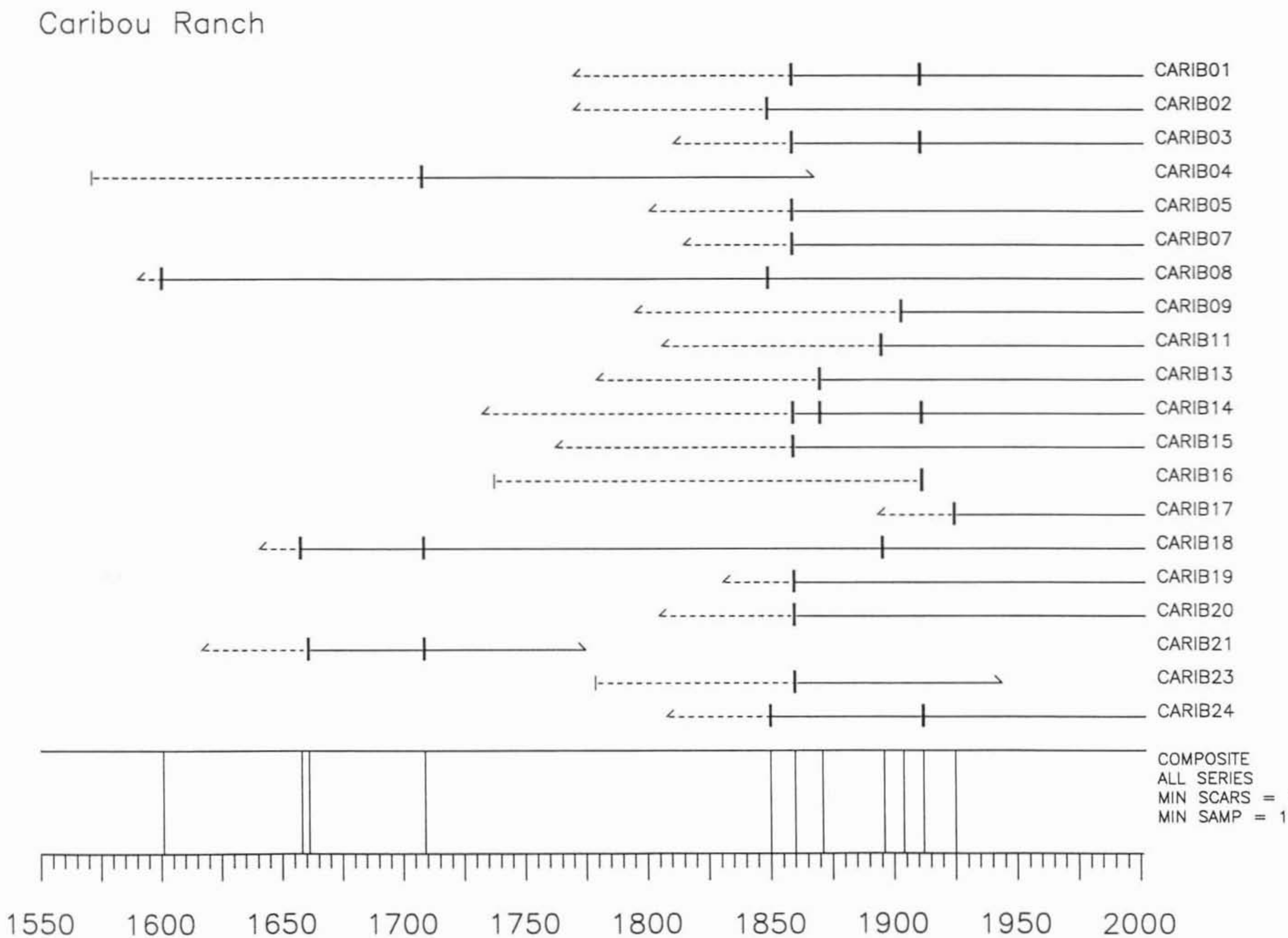


Figure 5. Composite fire-scar record for Caribou Ranch indicating fire years. Graphs were created using the FHX2 program. Each horizontal line represents an individual tree. Short vertical lines on each horizontal line indicate fire-scar dates. Dashed lines indicate years prior to the first fire-scar date on each individual sample.



Caribou Ranch
CARIB01
CARIB02
CARIB03
CARIB04
CARIB05
CARIB07
CARIB08
CARIB09
CARIB11
CARIB13
CARIB14
CARIB15
CARIB16
CARIB17
CARIB18
CARIB19
CARIB20
CARIB21
CARIB23
CARIB24
COMPOSITE
ALL SERIES
MIN SCARS = 1
MIN SAMP = 1
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

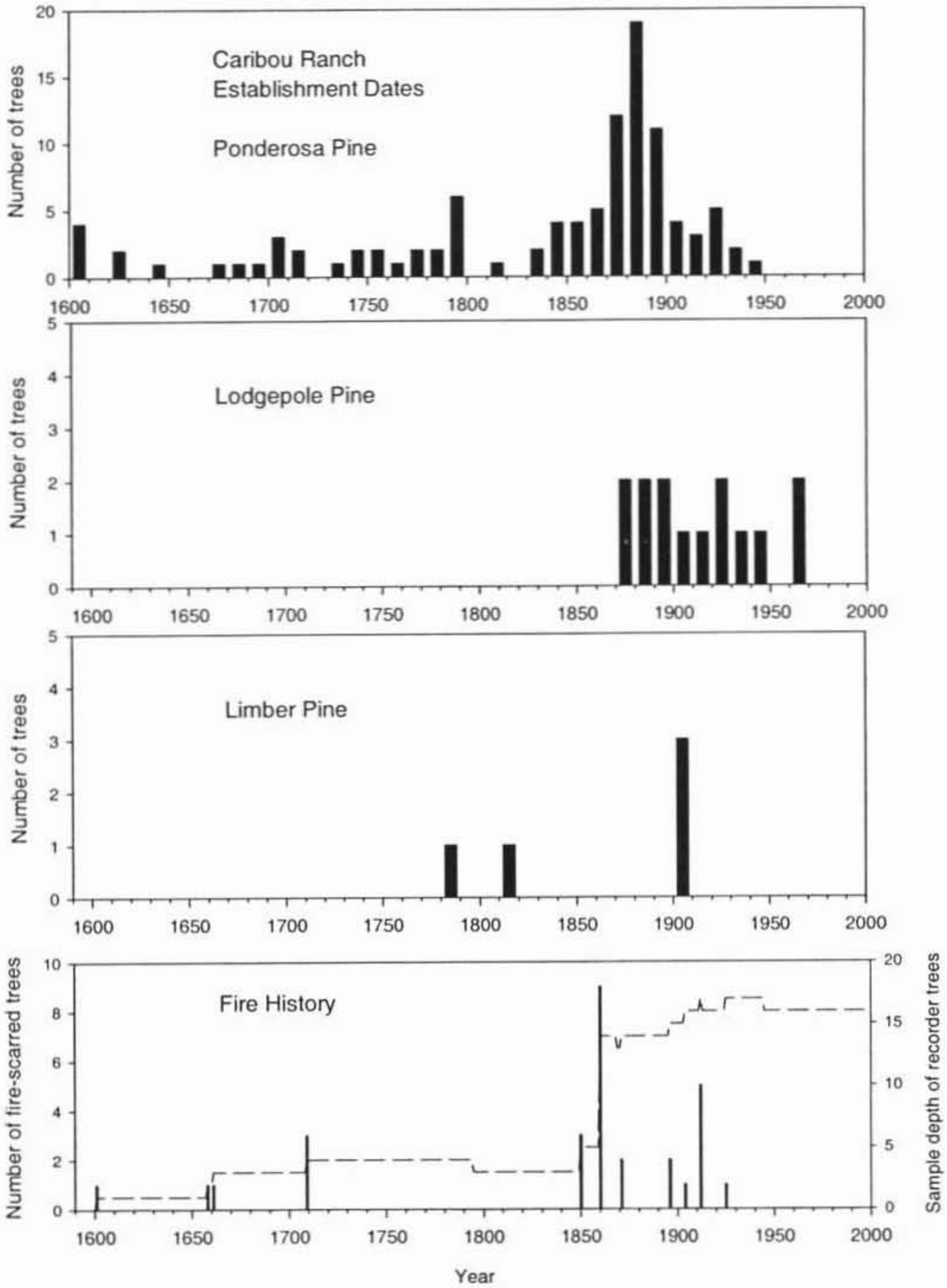


Figure 6. The top graph represents the age structure of live trees (> 4cm DBH) for the Caribou Ranch study site. The histogram shows the age structure of ponderosa pine, lodgepole pine and limber pine trees. The bottom graph represents the fire history in the same sampling areas. The vertical bars indicate the percentage of trees fire-scarred (left axis) during an individual fire year. The dashed line represents the number of recorder trees (right axis) through time. Recorder trees are previously fire-scarred trees that have an exposed scar and will subsequently record fires that occur at the site.

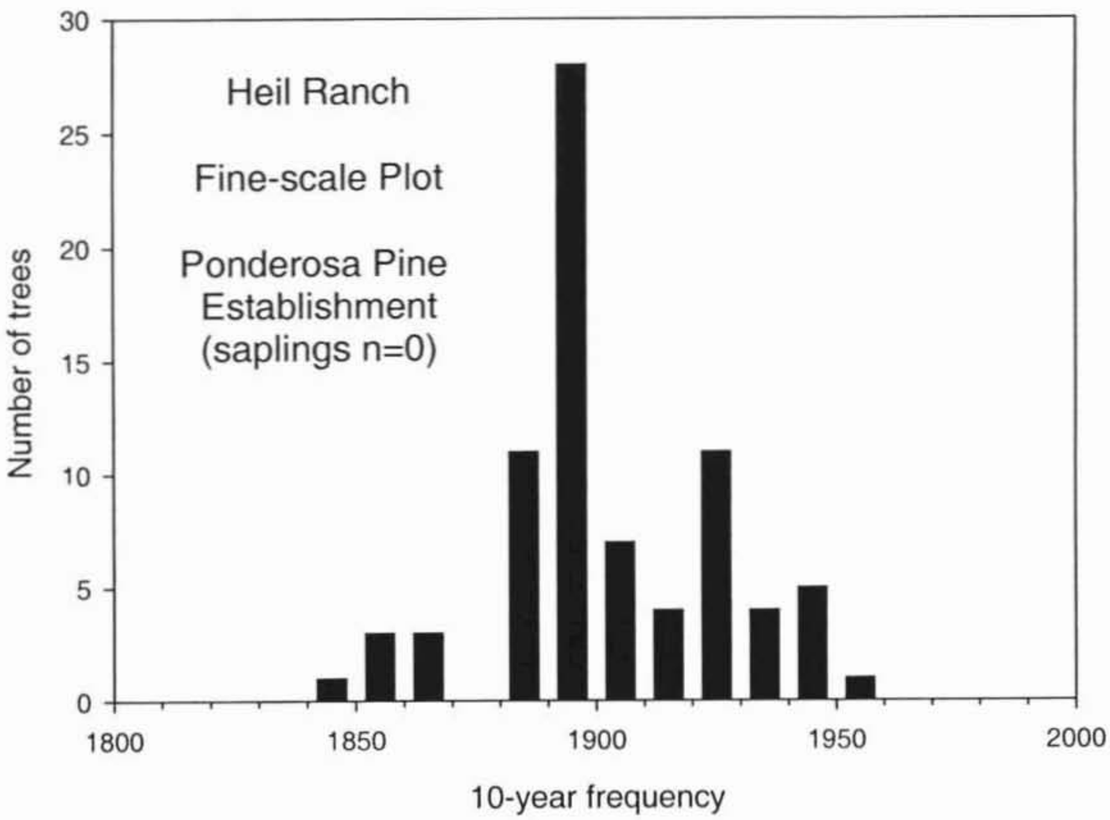


Figure 7. The graph represents the age structure of live trees (> 4cm DBH) for the random plot in the Heil Ranch study site. The histogram shows the age structure of ponderosa pine trees.

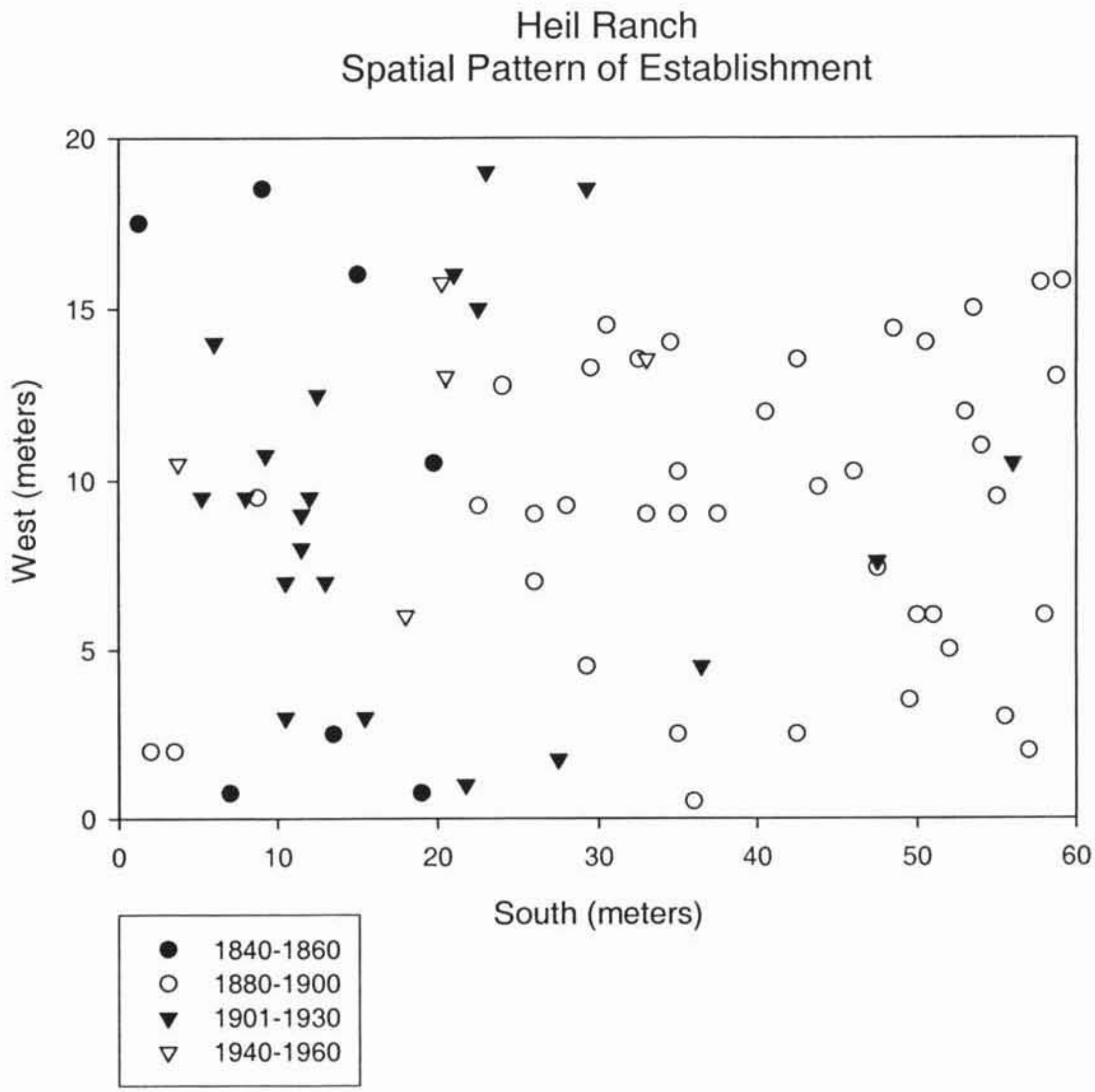


Figure 8. The graph represents the spatial pattern of tree cohort ages in the 20 by 60 meter random plot at Heil Ranch. There were no saplings in the plot.

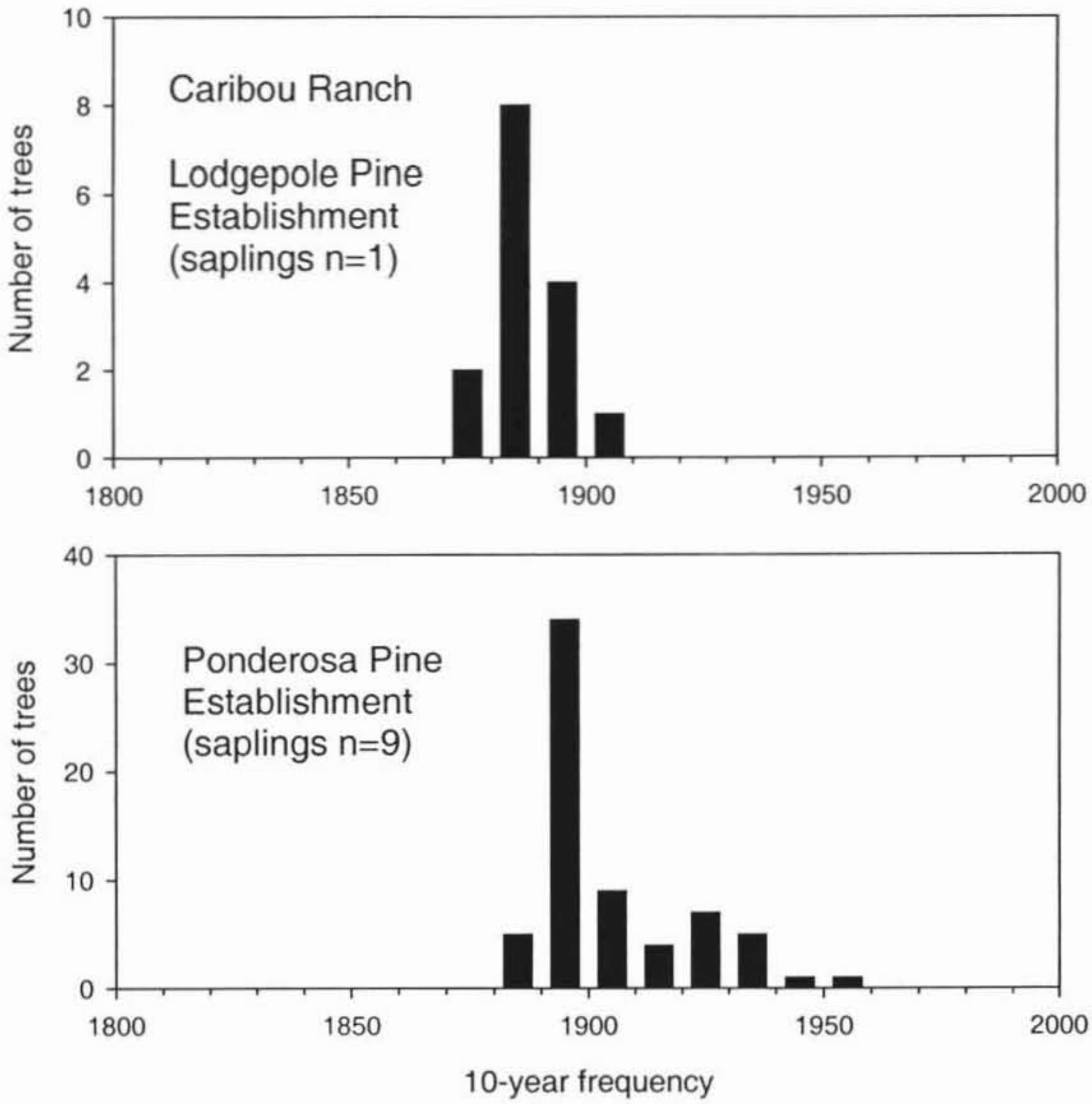


Figure 9. The graph represents the age structure of live trees (> 4cm DBH) for the random plot in the Caribou Ranch study site. The histogram shows the age structure of ponderosa pine and lodgepole pine trees.

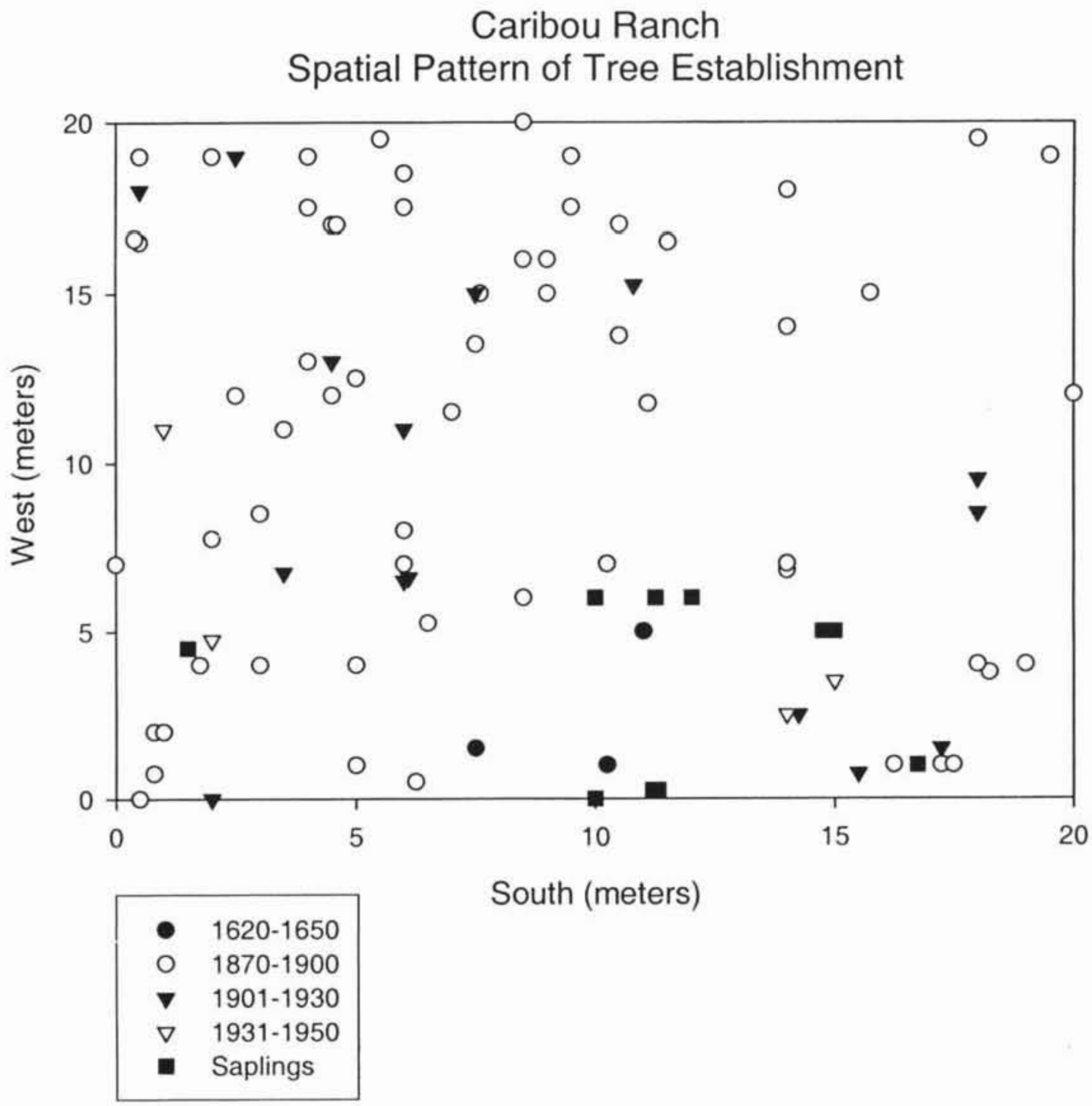


Figure 10. The graph represents the spatial pattern of tree cohort ages and saplings in the 20 by 20 meter random plot at Caribou Ranch.

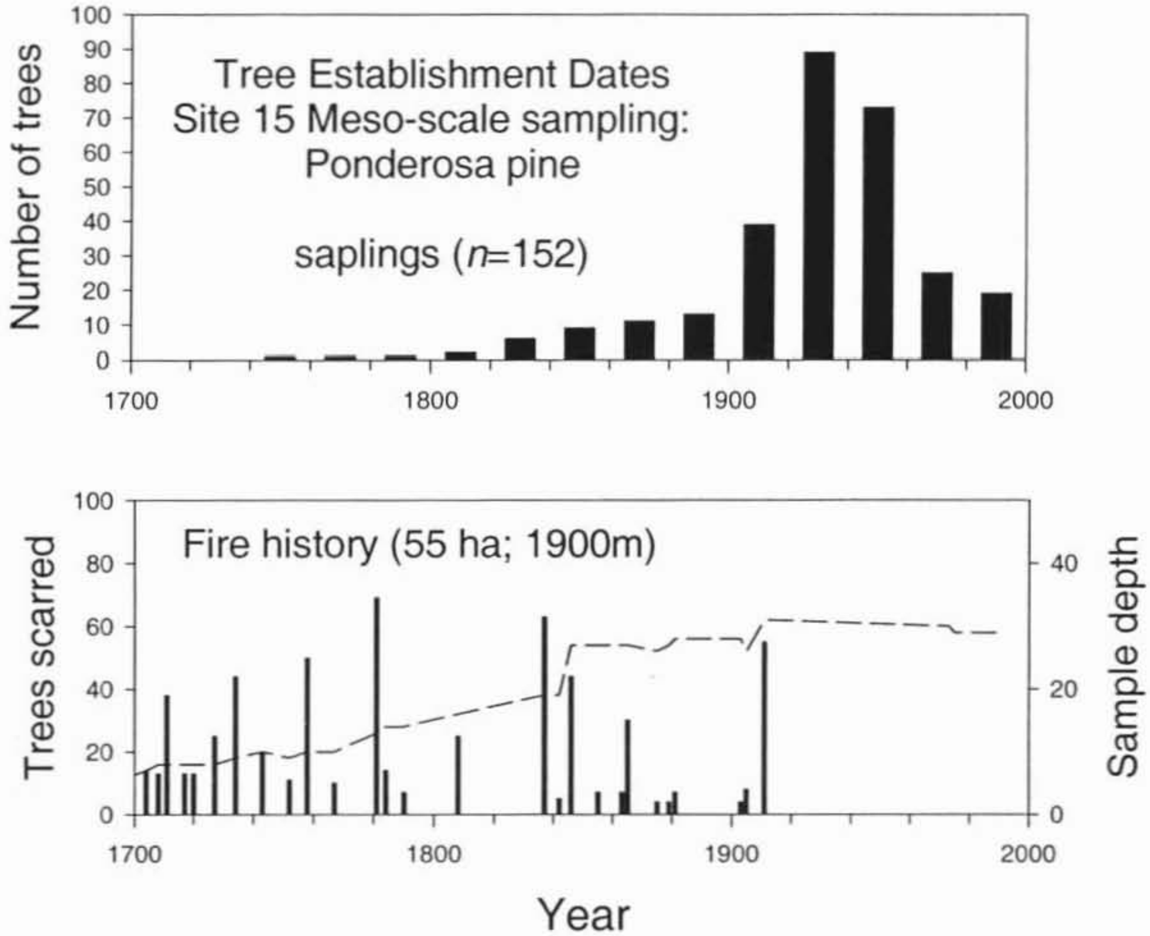


Figure 11. The top graph represents the age structure of live trees (> 4cm DBH) for the Eldorado Springs study site. The histogram shows the age structure of ponderosa pine trees. The bottom graph represents the fire history for the Eldorado Springs area. Specific details on the fire history are cited in the Veblen et al. 1996 report to the City of Boulder (Site 15). The vertical bars indicate the percentage of trees fire-scarred (left axis) during an individual fire year. The dashed line represents the number of recorder trees (right axis) through time. Recorder trees are previously fire-scarred trees that have an exposed scar and will subsequently record fires that occur at the site.

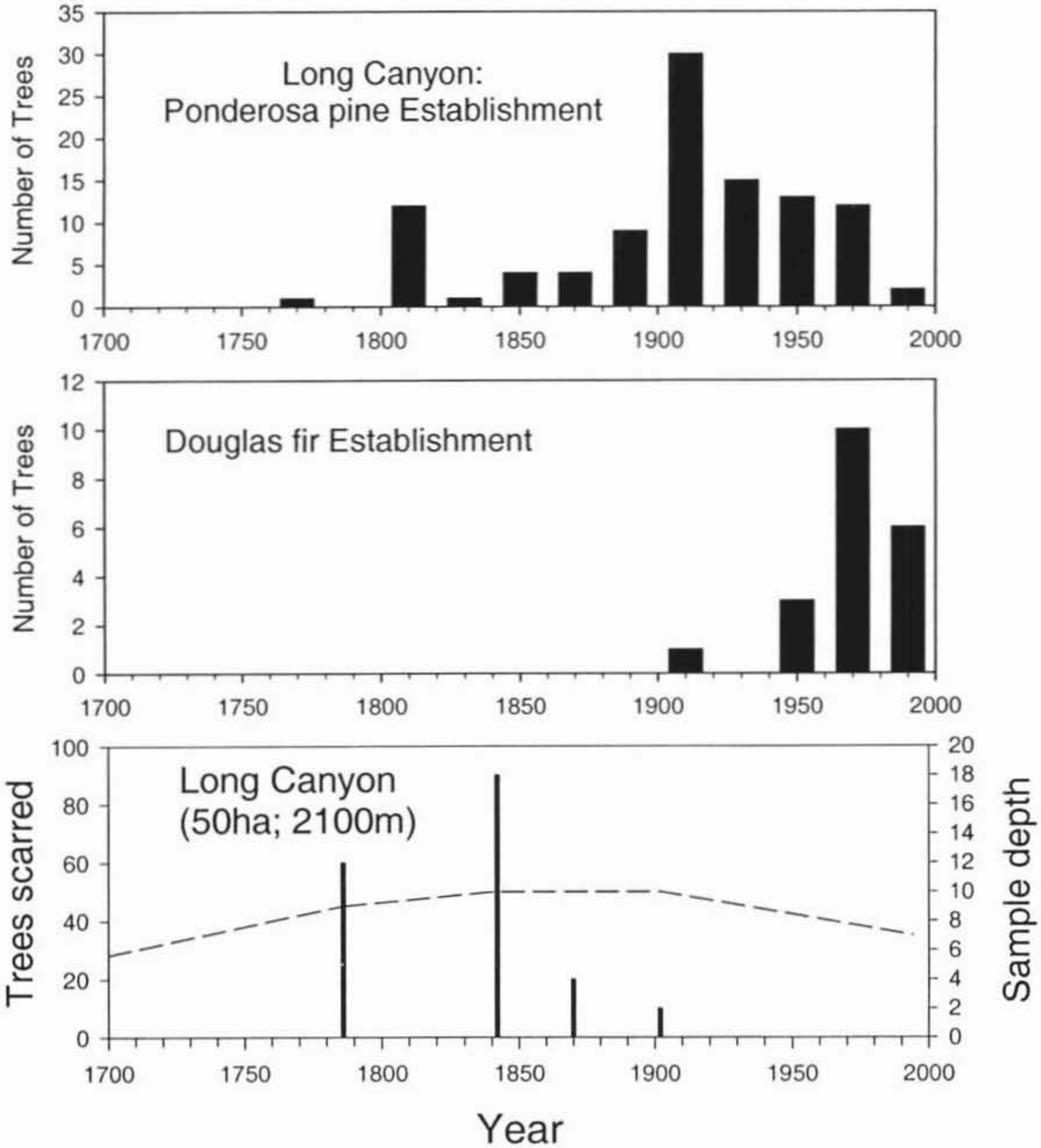


Figure 12. The top graphs represent the age structure of live trees (> 4cm DBH) for the Long Canyon study site. The histogram shows the age structure of ponderosa pine and Douglas fir trees. The bottom graph represents the fire history for the Long Canyon area (Site 11 in Veblen et al. 1996). The vertical bars indicate the percentage of trees fire-scarred (left axis) during an individual fire year. The dashed line represents the number of recorder trees (right axis) through time. Recorder trees are previously fire-scarred trees that have an exposed scar and will subsequently record fires that occur at the site.

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