Historical forest structure and fire history in lower elevation ponderosa pine forests of Hall Ranch and Heil Valley Ranch Open Spaces, Boulder County, northern Front Range, Colorado

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Abstract
Site-specific information on historical forest structure is essential for informing restoration treatment prescriptions in fire-adapted ecosystems and for assessing success of treatments at achieving desired conditions. We reconstructed historical (ca. 1860) forest structure and fire histories in 14 0.5 ha plots in lower elevation (1900 to 2100 m) ponderosa pine forests in the northern Front Range of Colorado. Fires recorded by trees in two or more plots from 1667 to 1859 occurred on average from 8 to 15 years depending on scale of analysis from individual plots to the two study areas combined (~3300 ha). Reconstructed stand structures in 1860 were diverse across both landscapes, with estimated tree densities that ranged from 0 to 330 trees ha^{-1} (TPH), estimated basal areas (BA) from 0.0 to 18.4 m^2 ha^{-1}, and estimated quadratic mean diameters (QMD) from 12.8 to 42.8 cm. All 1860 trees were ponderosa pine. Over half of the evidence of the 1860 forest came from stumps, harvested after Euro-American settlement. Current stands based on living trees ≥4 cm diameter at breast height are more dense (175 to 1010 TPH) with generally larger BA (4.4 to 23.1 m^2 ha^{-1}) and smaller trees (QMD 15.7 to 28.2 cm). Trees were significantly aggregated in 69% of plots where trees were present in 1860, with 0% to 91% of trees occurring in groups (defined as ≤6m of another tree) and 0 to 60 groups ha^{-1}. Reconstructions provide quantitative metrics of historical forest structural patterns and the fire regime to help guide forest restoration prescription development, implementation, and evaluation in these and similar ponderosa pine forests across the northern Colorado Front Range.

1. Introduction

Forests dominated by ponderosa pine (*Pinus ponderosa*) in the Front Range of Colorado have experienced a series of wildfires over the past two decades that have continued to increase in both area burned and burn severity (Graham 2003, FRFTP 2006, Graham et al. 2012). These fires have damaged critical watersheds, destroyed homes and infrastructure, and worst of all led to loss of life of homeowners caught in their paths. A principle factor contributing to extensive areas of high burn severity is a high degree of vertical and horizontal tree continuity at both stand and landscape scales (FRFTP 2006). Although there is debate as to how much canopy continuity has changed in higher elevation ponderosa pine and mixed-conifer forests (>~2300 m elevation; e.g., Baker et al. 2007), there is substantial agreement that tree densities and landscape coverage of denser stands in lower elevation ponderosa pine forests (<~2300 m) are outside their historical ranges of variability (HRV; Kaufmann et al. 2000, 2001, Huckaby et al. 2001, Brown et al. 2001, Veblen and Donnegan 2006, FRFTP 2006, Sherriff and Veblen 2006, 2007, Baker et al. 2007). Cessation of largely low-intensity surface fires coupled with harvest of larger and older trees since Euro-American settlement in the latter half of the 1800s have encouraged the formation of ladder fuels, resulted in denser stands of younger and smaller trees, contributed to homogeneous canopy structure across landscapes, and resulted in the loss of meadows and openings that contributed to landscape-scale patch diversity (FRFTP 2006). These conditions promote active crown fires by allowing fire to more readily transition from surface to aerial fuels and to burn more extensively across landscapes when weather conditions are conducive to extreme fire behavior.

Recognition of stand- to landscape-scale changes in forest structure from HRV has led to increasing efforts at landscape-scale ecological restoration of Front Range ponderosa pine forests (Brown et al. 2001, FRFTP 2006, Clements and Brown 2011). Goals of these restoration efforts are to mitigate wildfire hazard in the rapidly expanding wildland-urban interface and to increase the ecological resilience of these forests to future wildfires, bark beetle outbreaks, and climate change. Quantitative data on both nonspatial (tree species composition, densities, and basal areas, and individual tree sizes and ages) and spatial (numbers and characteristics of tree groups) structure of historical forests provide models for foresters and ecologists to develop operational objectives for silvicultural restoration treatments (e.g., Fulé et al. 1997, Churchill et al 2013, Reynolds et al. 2013). Such data also help to evaluate the success of treatments intended to restore more resilient forest conditions (Churchill et al. 2013). However, unlike other regions with ponderosa pine forests, such as the southwestern US (e.g., Fulé et al. 1997, Friederici 2003, Abella and Denton 2009, Sanchez Meador et al. 2011, Reynolds et al. 2013), such quantitative data are rare or nonexistent for Front Range forests (Clements and Brown 2011).

In response to this lack of data and demands from managers and stakeholders for science-based restoration prescriptions, the Front Range Forest Reconstruction Network (FRFRNet) was initiated in spring of 2012. The main goals of FRFRNet are to reconstruct historical stand structures, fire regimes, and tree spatial patterns within stands, and to relate these conditions to environmental gradients (latitude, elevation, moisture, aspect, soils) across the Front Range ponderosa pine zone. The research approach used in FRFRNet is to characterize nonspatial and spatial aspects of historical forest structure from a series of 0.5 ha plots located in discreet study landscapes where restoration activities are expected to occur in upcoming years, such that site-specific metrics will be available to inform restoration prescription development for individual treatment units. Major foci of current restoration efforts in ponderosa pine forests include not only structural elements of the historical forests but also how these elements relate to one another across environmental gradients and in response to changing disturbance and climate forcings (Abella and Denton 2009, Larson and Churchill 2012, Churchill et al. 2013). FRFRNet study landscapes are located across ranges of environmental gradients in elevation, latitude, and physiographic conditions where ponderosa pine occurs in the Front Range.

In this paper, we describe results from two FRFRNet study landscapes in the northern Front Range, Boulder County's Hall Ranch and Heil Valley Ranch Open Spaces (Figure 1). Intensive restoration treatments are being done in these areas at present, and more are planned for coming years. Specific objectives for this study are: 1) to reconstruct historical fire regimes, including fire timing, seasonality, and relationships with climatic and human forcings; 2) to reconstruct historical (ca. 1860) nonspatial stand structures, including tree species composition, densities, basal areas, and size and age distributions; and 3) to reconstruct historical spatial stand structures at the scale of the 0.5 ha plots, including the number and characteristics of tree groups and their spatial arrangement. We chose 1860 as the date to reconstruct historical forest conditions because it both marks the beginning of intensive Euro-American settlement and attendant land use changes in Boulder County and is the approximate earliest germination date (ca. 150 years ago) when trees begin to take on old-age morphological characteristics (Huckaby et al. 2003). This latter criterion allows us to have confidence in being able to use extant forest evidence to reconstruct historical forest structure. Although caveats are necessary due to an attenuated record over time, reconstructions of stand and forest conditions across the two study landscapes are generally robust and can serve as useful models to guide future restoration of stand structures and reintroduction of fire regimes in these and comparable ponderosa pine ecosystems across the northern Colorado Front Range.

2. Methods

2.1. Study areas

The study was conducted at Hall Ranch (1298 ha) and Heil Valley Ranch (1993 ha) Open Spaces in the Front Range of northern Colorado (Figure 1). These areas have been owned and managed by the Boulder County Parks and Open Space (BCPOS) department since the early 1990s. Elevations in the study areas range from ~1675 m on the margins of the shortgrass steppe to the east to ~2300 m where they meet mainly Arapaho-Roosevelt National Forest lands to the west. The study areas comprise a series of sedimentary hogbacks and cuestas forming steep ridges and valleys along with broad undulating benches on the uplands. Soils are mainly coarse textured and shallow. Both areas contain forests and woodlands dominated in most areas exclusively by ponderosa pine, along with large areas of grasslands and shrublands (Figure 1). Forest cover decreases to the east as elevation decreases into the shortgrass steppe of the eastern Colorado plains. Douglas-fir (*Pseudotsuga menziesii*) increases with elevation and in more moist, productive locations, especially north-facing slopes. Rocky Mountain juniper (*Juniperus scopulorum*) is a minor component, restricted primarily to lower elevations and drier locations. Woodland and open forest understories consist of abundant grasses and forbs. Localized areas where shrubs dominate the understory are less common. In denser forests, understory plants are sparse, replaced with often abundant needle litter. Large rock and boulder outcrops also are present, especially at Hall Ranch to the north. Annual rainfall for the city of Boulder (1660 m) located ~20 km south of the southern edge of the Heil Valley Ranch study area averages 480 mm. Mean annual temperatures for Boulder range from 17.9°C maximum to 3.4°C minimum.

Prior to Euro-American settlement, the northern Front Range was occupied by Ute tribes who dominated much of the central Rocky Mountains since at least the late 1600s (Wyckoff 1999). Native peoples may have influenced fire frequency and intensity, at least on local scales, but their role is largely unknown (Baker 2002). The region was intensively settled by Euro-Americans following a gold rush beginning in 1859. It has been estimated that more than 100,000 people moved to the northern Front Range in the early 1860s (Buchholtz 1983). Much of that movement centered on the cities of Boulder, Golden, and Denver just south of our study areas. Timber harvest, livestock grazing, and mining were ubiquitous and widespread starting in the early settlement period and continued through much of the twentieth century (Veblen and Lorenz 1991, Veblen and Donnegan 2006). Hall and Heil Valley Ranches were no exception, with histories of livestock grazing, logging, and stone quarrying dating from early Euro-American settlement until just prior to their acquisition by Boulder County. Today, the two study areas are used mainly for recreation and scientific research.

Because of historical land use and fire management practices, these two landscapes are susceptible to high-severity fire. Since the late 1990s several large, severe wildfires burned just to the north (Big Elk Fire) and south (Fourmile Canyon and Overland Fires) of the two areas. Although the Overland Fire did burn a portion of the south end of Heil Valley Ranch in 2003, Heil Valley and Hall Ranch Open Spaces remain one of the last large, contiguous areas in the northern Front Range that has not experienced wildfire during the past 20+ years (FRFTP 2006). Concern among BCPOS managers, local elected officials, and community residents is high that these areas are vulnerable to uncharacteristic wildfire and in need of restoration treatments, including reintroduction of characteristic wildfire or prescribed fire. Forest managers in particular desire to restore forest stands consistent with historical conditions, and stand to benefit from historic forest reconstruction study results.

2.2. Field methods

Field work was conducted in 2012 and early 2013 in 14 0.5 ha (70.7 m x 70.7 m) plots in Hall (HA plots) and Heil Valley Ranch (HE plots) Open Space study areas (Figure 1, Table 1). Plot locations were determined by first randomly locating potential plot locations in areas currently occupied by forest cover and that had not experienced a recent wildfire that would have resulted in destruction of evidence of pre-settlement trees. Plots were sampled if the potential plot location met the following criteria: 1) plot center was located or could be moved no more than ~50 m to encompass an area of 0.5 ha that was of relatively uniform slope and aspect; and 2) the plot contained a mean slope steepness ≤40%. The latter criterion was necessary to characterize forest structure in areas amenable to mechanical restoration treatments. All plots are located below 2100 m and fall into the Front Range lower montane forest zone (Peet 1981, Veblen and Donnegan 2006).

Our goal in each 0.5 ha plot was to characterize nonspatial and spatial stand structures in 1860 prior to intensive land use impacts. Since we could not know *a priori* which trees were alive in 1860, we mapped and collected data from all trees in a plot that met one of the following three criteria: 1) a living tree ≥25 cm diameter at breast height (DBH); 2) a living tree <25 cm DBH if it exhibited old-age morphological characteristics; or 3) a remnant tree (stump, log, or snag). We refer to any tree that met one of these criteria as “pre-settlement”, although we knew that some were not. The 25 cm DBH cutoff for trees alive in 1860 was based on review of dendrochronologically crossdated age and size data for ponderosa pine trees compiled from several previous studies in Front Range forests (Kaufmann et al. 2000, 2001, Huckaby et al. 2001, and other unpublished data). These previously collected age-size data documented that ≥95% of all trees >150 years old were ≥25 cm DBH at time of sampling (although many trees ≥25 cm DBH were < 150 years old). Morphological characteristics used to identify older trees are those that indicate changes that occur naturally in ponderosa pines as they age. These characteristics included bark that was relatively smooth, un-fissured, and predominately orange or gray rather than black; a relatively open crown with primarily large diameter branches and fewer fine branches; a flattened canopy indicating weakening apical dominance as the tree reaches its maximum height for the site; a damaged or dead top; a relatively high canopy base height; and evidence of fire scarring (Huckaby et al. 2003, Abella and Denton 2009). We assigned a category of “young”, “transitional”, or “old” to each pre-settlement living tree in an effort to further refine morphological characteristics with tree ages (details in next section). We also recorded species and DBH for each living sample tree. For remnant pre-settlement trees (criterion 3), we recorded species, status (stump, log, or snag), diameter at sample height (DSH ; ~30 cm above ground level) and whether the DSH measurement was for the bark, sapwood, or heartwood only (eroded). Many of the remnants sampled were eroded stumps for which we were not able to measure DBH.

We next established four 500 m^2 circular subplots in the center of each quadrant of the main 0.5 ha plot. Quadrants were defined by cardinal directions. We had four goals in each quadrant subplot: 1) to collect increment cores and cross sections from pre-settlement trees to characterize age structure and to refine age/size/morphology relationships of living pre-settlement trees over the entire 0.5 ha plot; 2) to measure DSH in addition to DBH on living pre-settlement trees to develop a plot-level DSH/DBH regression with which to estimate DBH for remnant trees; 3) to characterize species, age, and density of "post-settlement" living trees ≥4 cm and <25 cm DBH and without old-age morphological characteristics (i.e., trees that did not meet either criteria 1 or 2 above for a pre-settlement tree); and 4) to determine height of two dominant living pre-settlement trees in each subplot (if present) for estimation of site indices (SI; Moberg 1956). For goal 1, increment cores were collected from all living pre-settlement trees and cross sections were cut with a chainsaw from all remnant trees ~30 cm height above ground level. Increment cores had to be no more than an estimated ~5 rings from pith to minimize pith offset for later determination of pith dates (e.g., Brown et al. 2008). For goal 3, we collected increment cores at ~30 cm above ground level from the five post-settlement trees nearest to subplot center and measured distance to subplot center for the farthest individual for calculation of densities, ages, and composition of post-settlement trees in each quadrant. Species, DBH, and DSH of each of these trees were also recorded.

In addition to cores and cross sections from the four subplots, we collected cross sections from any other fire-scarred trees found in the main plot. We also sampled any fire-scarred trees found within ~100 m of the main plot to supplement the fire-scar record from the plot itself. For these trees, we recorded GPS location, species, tree status (living, stump, log, or snag), and cut height of samples.

2.3. Laboratory methods and analyses

2.3.1. Plot environmental characterization

We characterized environmental variation between plots by their elevations, topographic relative moisture contents (TRMI), and site indices (SI; Table 1). TRMI is the sum of four topographic parameters that affect soil moisture holding capacity: aspect, slope, topographic position, and slope shape (Parker 1982). Higher values indicate relatively moister conditions. These parameters were recorded in the field for each plot. SI is an estimate of overall average site productivity of site index trees measured in subplots (Moberg 1956). Higher SI indicates relatively more productive stands.

2.3.2. Fire and stand age histories

All increment cores and cross sections were prepared, surfaced, and crossdated using standard dendrochronological methods (Speer 2010). We used locally developed master chronologies for visual and skeleton plot crossdating of samples. On increment cores and cross sections that did not include pith but inside ring curvature was visible, pith dates were estimated using overlaid concentric circles of varying circumferences that take into account both average inside ring widths and estimated distance to pith (e.g., Brown et al. 2008). Only after crossdating of ring series was complete did we assign dates for fire scars. We also assigned seasonal positions for fire scars based on locations within annual ring boundaries (Dieterich and Swetnam 1984). Dormant season scars (recorded between two rings) were usually dated to the prior year (i.e., to have been fall fires after growth ended for the year) because of a predominance of latewood scars when recorded within rings. A few dormant season scars were dated to the latter year (i.e., to have been spring fires before growth began) because of early-earlywood scars recorded on other trees for that same year. Any tree-ring samples that could not be crossdated were not used in subsequent analyses.

Fire-scar dates were compiled into composite chronologies for each plot using program FHX2 (Grissino-Mayer 2001). Fire-scar dates used in the composites were those recorded on ≥2 trees in either study area. This minimum filtering was intended to eliminate false positives (i.e., scars formed by factors other than fire; Brown et al. 2008). We defined a period of analysis within which to estimate fire frequency based on a minimum of two plots in each study area recording fires. Fire frequencies for each study area and for both areas combined were estimated for the period of analysis based on plot composite chronologies.

We examined fire-climate relationships using superposed epoch analysis (SEA; e.g., Sherriff and Veblen 2008). We compared average summer (June-August) Palmer Drought Severity Indices (PDSI) reconstructed from tree rings (Cook et al. 2004) for fire dates recorded in at least two plots in either study during the period of analysis. The PDSI series used is from grid point 131 (105.0°W, 40.0°N) located in north-central Colorado (Cook et al. 2004).

Pith dates for trees sampled in the subplots were compiled into 5-year age histograms for comparison of age structure within and between plots and with the fire chronologies. We did not correct for the age to coring height but use 30 cm height pith dates from increment cores or cross sections for age structure analysis.

2.3.3. Nonspatial stand structure

Tree densities (TPH; trees ha^{-1}), species composition, basal areas (BA; m^2 ha^{-1}), and quadratic mean diameters (QMD; cm) for each plot in 1860 were estimated based on ages, sizes, and species of pre-settlement trees alive in 1860 in the four subplots. Estimates of 1860 stand structure are robust since all potential pre-settlement trees in subplots were crossdated. We therefore know which of the subplot trees were alive in 1860 and, using the increment core or cross section collected from the tree, can estimate tree size at 30 cm height at that date. Note, however, that we may be missing evidence that was present in 1860 but has since decayed in the 150+ years since (see further comments in discussion; see also discussions in Brown and Cook 2006, Brown et al. 2008). Tree density and species composition were determined from the number and species of trees alive in the four 500 m^2 subplots in 1860 multiplied by 5 (to scale to unit area). DSH at 1860 of each of these trees was then estimated to determine tree DBH and tree and stand BA. For living trees or recently dead trees with bark or sapwood that were alive in 1860, we determined the ratio of core or section radius at 1860 to total radius multiplied by field-measured DSH to estimate 1860 DSH. For stumps or other remnant trees missing sapwood but with pith dates before 1860, we either were able to measure DSH in 1860, or if the outside date was earlier than 1860, assumed that the tree was alive in 1860. The majority of remnants sampled in all plots were eroded stumps (with only heartwood) with outside dates sometime before 1860. We assumed that these were cut sometime after 1860, but were present in the 1860 forest. For these trees, we used a regression equation relating ratio of heartwood radius to total tree radius measured on living trees in the subplots to estimate DSH in 1860 (sensu Brown and Cook 2006, Brown et al. 2008). The regression equation was derived from living trees sampled over both study areas ($DSH_{1860} = DSH_{heartwood}^{0.52} * 9.2$; n = 122; $R^2 = 0.78$; $\alpha < 0.001$). Tree DBH was then estimated from the reconstructed DSH measurements using plot-specific linear regression equations derived from DBH/DSH measurements from living sample trees in the subplots: DBH = DSH * Y. Y varied by plot but ranged from 0.83 to 0.88 (all regression models significant at $\alpha = 0.001$.). Tree BA was then calculated from the estimated DBH. Total plot BA in 1860 was then determined as the sum of individual tree BA in the four subplots multiplied by 5 (to scale to unit area). QMD was calculated as the square root of plot BA divided by plot TPH multiplied by 0.0000785.

We next calculated tree densities, species, basal areas, and quadratic mean diameters of the current (2012) forest based on living trees in the subplots. TPH of the current forest was calculated as the sum of the living pre-settlement trees in subplots scaled to unit basis plus the average of post-settlement tree density from the four subplots. Note, however, that this measurement of density does not include trees <4 cm DBH since these were not measured in subplots, Thus, these data are not the same set of data as the estimated historical forest structure which includes all tree present in subplots in 1860 regardless of size. Furthermore, because of the difference in evidence used to develop the two data sets (measurements of living trees vs. reconstructed data) the two data sets are not subjected to the same level of precision and should not be considered to be directly comparable. Rather our goal with describing the current forest is to compare general trends in nonspatial structure from the historical forest. TPH of the post-settlement trees was estimated as the number of trees within a circular plot of the radius of the farthest tree sampled in each subplot scaled to a per ha basis (Brown et al. 2008). BA of the current forest was then calculated from DBH measurements of both pre- and post-settlement trees in the subplots. QMD for the current forest was estimated from the plot BA and density as was done for the 1860 forest. Again, note that QMD does not include the smallest components of the current forest (i.e., trees <4 cm DBH) and therefore is not directly comparable to the 1860 structural estimates since all trees are included in those regardless of DBH.

2.3.4. Spatial stand structure

A major goal of this study is to estimate spatial patterns of trees present in 1860, especially the presence and characteristics of tree groups. Groups are defined as at least two trees with interlocking crowns, which we further define as ≤6 m between center points of tree stems (e.g., Larson and Churchill 2012). We first had to estimate which of the sample trees were present across the entire plot in 1860. This was done using tree status (remnant or living), morphology of living trees (young, transitional, or old), condition of remnants (whether bark, sapwood, or only heartwood was present), and DBH measured in the field, coupled with crossdated ages of subplot trees. For living and remnant trees sampled in subplots, we knew which were present in 1860 based on crossdated tree ages. For living trees sampled over the rest of the plot, we used both morphology classifications (young, transitional, and old) and DBH/age regressions derived from crossdated living trees in the subplots. We assigned all "old" living trees to the 1860 forest based on their morphology. We then used a DBH/age regression equation derived from living trees sampled over both study areas to assign "transitional" living trees to either pre- or post-1860 status based on their measured DBH and the site index of the plot (DBH_{1860} = age * 0.085 + SI * 1.275; n = 679). The size cutoff for assigning a tree to the 1860 forest (age = 152 years in 2012) ranged from 22.7 to 32.9 cm depending on plot SI. Trees classified in the field as "young" according their morphology were not included in the 1860 forest. Eroded remnant trees (i.e., with only heartwood remaining) were assigned to the 1860 forest based on an assumption that all were older than 1860. Most of these were stumps, harvested presumably sometime in the late 1800s or early to middle 1900s. Other remnant trees (with bark or sapwood present) were assigned to the 1860 forest based on the DBH/age regression equation.

Once we had assigned trees to the 1860 forest for each plot, we then estimated both global and local spatial tree patterns (per recommendations in Larson and Churchill 2012). We used the *L(d)* statistic from program PASSaGE, version 2 (Rosenberg and Anderson 2011), to estimate global spatial structure of trees in each plot in 1860. *L(d)* is a linear transformation of Ripley's *K* statistic (Ripley 1977) with an expected value of zero when spatial distributions are random. Significant negative values indicate aggregation of trees at varying spatial scales while significant positive values indicate regular spacing of trees. Settings used to calculate *L(d)* in PASSaGE were 1m step distances, 18 m maximum distance (25% of the plot maximum distance of 70.7 m), an edge correction, and 95% confidence intervals to test for significant departures using 1000 random permutations of x/y coordinates in the plot. We next calculated local spatial patterns using numbers and characteristics of tree groups (Abella and Denton 2009). We calculated percentage of trees in groups, modal and maximum group sizes, and number of groups per hectare for each plot.

3. Results

3.1. Fire and stand age histories

A total of 925 trees were crossdated from the 14 plots, 893 with pith or from cores where pith could be estimated (97% of crossdated trees; Figure 2). An additional 19 trees were sampled (2% of all cores or cross sections collected) but could not be crossdated, mostly from remnant stumps that contained too few rings to be able to find the dating. The oldest living tree was found in plot HE13 with a pith date of 1554. A number of older remnants were found, including three dating into the 1400s. The earliest pith date recorded was 1448 on a stump from plot HA01.

A total of 298 of the 925 crossdated trees (32%) were present in plots in 1860. Of these, 135 were still living in 2012 (19% of a total of 717 living trees sampled) and 163 were remnants (78% of a total of 208 remnants). The majority (142 trees; 87% of the 163 total) of the remnant trees alive in 1860 were eroded stumps, with only heartwood remaining. The majority (100 trees; 74% of the 135 total) of the living trees present in 1860 were from a single plot, HE18 (Figure 2). Eroded stumps were found in all plots except HE18, HE22, and HA03 (the latter of which has no trees present in 1860 at all).

Fire-scarred trees were found in or near all plots except for HA03, with a total of 83 fire scars analyzed (Figure 2). Fire scars were found almost exclusively on stumps or other remnant trees, with only four living or recently dead fire-scarred trees sampled in either landscape. Dates of fires recorded by trees in ≥2 plots are at the bottom of Figure 2, with the last of these fires recorded in 1859. Three trees in plot HA01 recorded fire scars in 1867, which was the last certain fire date recorded in any of the plots. Several scars were found on individual trees during the rest of the nineteenth and early twentieth centuries, but we have excluded them from consideration as originating from fire since they were not recorded on more than a single tree.

We were able to determine location within the annual ring on 41 of the 83 total scars (49%). Thirty-four of these scars (83%) were either recorded in the latewood or as a late dormant season scar (after the growing season ended). Only seven scars (17%) were located in the early-earlywood or as an early dormant season scar (before the growing season began). No fire scars were recorded in the middle or late earlywood.

A period of analysis to determine fire frequency was defined from 1667 to 1859 (Figure 2). Fire dates recorded in 2 or more plots during the period of analysis (dates at bottom of Figure 2) were used to determine frequencies of fires that occurred within each study area, and frequency of fires that occurred in either landscape or only those recorded in both landscapes (Table 2). SEA of fire dates from 1667 to 1859 documented that fire years occurred on average during years with very dry summers (Figure 3). We saw no lagged relationships indicating wetter conditions prior to fire years.

3.2. Nonspatial stand structure

We mapped and collected data from a total of 1955 “pre-settlement” living and remnant trees in the 14 plots. The majority of trees were ponderosa pine, with only 72 trees (4%) either Douglas-fir or Rocky Mountain juniper. Of the crossdated trees, only two Douglas-fir trees were alive in 1860, both fire-scarred stumps from plot HE20 and both established in the early 1600s. However, both of these Douglas-fir trees were sampled outside of the subplots and therefore are not included in the 1860 nonspatial structure of the stand. No crossdated junipers pre-dated 1860.

Crossdated living trees from subplots confirms using the ≥25 cm DBH cutoff coupled with tree morphology for trees <25 cm DBH successfully captured nearly all of the trees alive in 1860 across all plots (Figures 4 and 5). Field classifications of morphology closely aligned with tree ages found on crossdated subplot trees (Figure 4). Only four of the 414 post-settlement living trees ≥4 cm and < 25 cm DBH (<1%) collected from subplots established before 1860 (Figure 5). Figure 5 also shows the generally poor relationship between age and DBH for the living trees and that use of morphological characteristics was necessary to more fully capture the 1860 trees in the subplots (Figure 4).

Reconstructed stand structure in 1860 varied considerably between plots, with estimated tree densities that ranged from 0 TPH in plot HA03 to 330 TPH in plot HE18 (Table 3). Basal areas in the 1860 forest ranged from an estimated 0.0 m^2 ha^{-1} in plot HA03 to 18.4 m^2 ha^{-1} in plot HA01. Tree diameter distributions also varied between plots (Figure 6), with several exhibiting multiple size classes that correspond roughly to age distributions (Figure 2). QMD ranged from an estimated 12.9 cm to 42.8 cm. All plots are forested today, with TPH of living trees ≥4 cm DBH ranging from 180 TPH in plot HA05 to 1010 TPH in plot HE21 (Table 4). Current plots also contain more basal area and smaller diameter trees than the reconstructed 1860 forests (Table 4).

3.3. Spatial stand structure

Similar to nonspatial structural metrics, reconstructed spatial patterns in 1860 varied considerably between plots (Table 5; Figure 7). A total of 69% of the plots where trees were present in 1860 exhibit aggregated distributions at some spatial scale, with most exhibiting grouping at some or all scales above 1 to 8 meters (Table 5). Four plots exhibited random patterns in tree arrangements. A range from 0% to 91% of all trees in plots occurred in groups. The majority of groups contained only 2 trees, with maximum group size ranging between 2 to 24 trees (Table 5).

4. Discussion

4.1. Fire history

As in ponderosa pine forests throughout most of its range, frequent surface fires ceased coincident with Euro-American settlement. The last fire recorded in more than one plot in our study areas occurred in 1859 (Figure 2), the year of the gold rush that brought intense settlement to the study areas along with accompanying changes in land use. Widespread livestock grazing was likely the initial cause of fire cessation, followed later by active fire suppression beginning in the early twentieth century (e.g., Brown and Wu 2005). Historical surface fires spread primarily through grass and herbaceous fuels, and intensive grazing disrupted historical patterns of fuel continuity across landscapes.

Fire frequencies at both plot and landscape scales (Table 2), fire-climate relationships (Figure 3), and fire seasonality are comparable to those found in previous fire history studies in northern Front Range ponderosa pine forests (Brown et al. 1999, Veblen et al. 2000, Sherriff and Veblen 2006). Fires occurred on average every 8 to 15 years depending on the spatial scale analyzed, either within plots or between the two study areas (Table 2). This average is also within the range of fire frequencies found by many other fire-scar based studies in ponderosa pine forests throughout its range (e.g., Swetnam and Baisan 1996, Fulé et al. 1997, Brown et al. 2008, Heyerdahl et al. 2011). However, a lack of spreading fires after 1859 is in contrast to some localities found in other studies in the northern Front Range (Veblen et al. 2000, Sherriff 2004). These other studies found both an increase in fires during the early settlement period and fires extending into the early twentieth century in some sites. It may be that we are missing some local fire dates in the late nineteenth or early twentieth centuries. For example, fire scars were recorded on two trees in plot HA01 in 1867. We also excluded several scars recorded on only single trees after 1859 that may have been caused by fire. However, we are confident that we collected enough fire-scarred samples in the late 1800s and early 1900s that we did not miss any fires that occurred between plots. Fires after 1859 likely burned over much smaller areas relative to fire extent prior to settlement and grazing. It is also possible that intensive grazing began earlier in this area than higher elevation sites (>~2100 m) where many of the previous studies were conducted, which resulted in more complete and earlier fire cessation than other locations on the Front Range. Other studies also were done farther south in Boulder County where mining was more prevalent, where increased burning and sparks from railroads may have contributed to increased fire frequencies in the early settlement period (Veblen and Lorenz 1991).

The lack of spreading fires after 1859 was followed by an increase in tree establishment in later decades of the nineteenth century (Figure 2). Fire cessation followed by abundant tree establishment and survivorship has been found in all previous studies of ponderosa pine forests throughout its range (e.g., Swetnam and Baisan 1996, Fulé et al. 1997, Brown and Cook 2006, Heyerdahl et al. 2011). Climate-driven episodic surface fires acted as a density-independent control on tree recruitment by killing a majority of seedlings and smaller saplings in most locations before they had a chance to reach maturity (Brown and Wu 2005). Once mature, a ponderosa pine tree is relatively immune to mortality from surface fires because of its high crown and thick bark. However, younger seedlings and saplings can be very susceptible to mortality from fire (Battaglia et al. 2009). With fire exclusion after 1859, surface fire was not a limitation on tree recruitment. In addition, livestock grazing would have reduced competitive pressure from grasses, further contributing to optimal conditions for establishment of ponderosa pine and Douglas-fir seedlings after settlement (e.g., Madany and West 1983).

4.2. Nonspatial stand structure

Stand structures in 1860 were very diverse across the two study areas (Table 3, Figure 6). Several of the plots were very open, with very few trees estimated to have been present in 1860. One plot, HA03, today is forested but was unforested in 1860. HA03 is adjacent to open grasslands, and it is likely that this entire area was grassland historically and has seen tree encroachment since settlement. On the other extreme, the densest stand was HE18 (Table 3, Figure 6), yet it was the fourth lowest in elevation and had the lowest site index of all plots (Table 1). HE18 is located on a southeast-facing, xeric, very rocky ridge near the margins of the Great Plains. Current herbaceous understory cover here is low compared to other plots or even surrounding areas on the ridge. We found fire-scarred trees in the vicinity of the plot but not in the plot itself. It is likely that trees are located in this area because they were relatively protected from past fires owing to the lower surface fuels and higher proportion of rocks. Trees in HE18 established in the 1700s and early 1800s, during the Little Ice Age when cooler and wetter conditions prevailed (Figure 2). HE18 also was one of only three plots that did not show any sign of previous harvest in the form of stumps, likely because of the short stature of the trees and generally poor growing conditions.

Historical tree densities and basal areas reconstructed by this study (Table 3) generally fall within ranges of similar metrics found by other studies in ponderosa pine forests from throughout the western United States, although average tree sizes tend to be smaller. Sánchez Meador et al. (2010) summarized structural characteristics from several studies in northern Arizona ponderosa pine forests that used both historical forest inventories and reconstruction methods. Historical tree densities found by these studies ranged from 12 to 255 TPH and basal areas from 4.6 to 18.8 m^2 ha^{-1}. Average diameters were bigger, with QMD ranging from 33.2 to 53.0 cm. Similar data from Brown and Cook (2006) found higher average densities (127 trees ha^{-1}) and basal areas (15.8 m^2 ha^{-1}) and much larger QMD (50.5 cm) in ponderosa pine forests of the Black Hills. Ponderosa pine forests in both the Southwest and Black Hills tend to be more productive, hence the larger trees in these landscapes relative to the northern Front Range.

We have made a number of assumptions in estimating trees present in each plot in 1860. Almost half of the crossdated trees that make up the 1860 forest structure estimates were stumps. Heartwood of ponderosa pine stumps can persist for several decades after bark and sapwood have decayed, but only depending on the amount of heartwood present in the tree at the time of harvest. Smaller stumps with correspondingly less heartwood harvested early in the settlement period may have completely disappeared by the time of our sampling (Brown and Cook 2006). We were able to estimate sizes of a number of smaller trees based mainly on living trees in plots (Figure 6). However, we may be missing many more small trees that have since disappeared from the plots, either through natural or human mortality and subsequent decay. In addition, Douglas-fir stumps decay more rapidly than ponderosa pine. We found only two Douglas-fir stumps that predated 1860, both of which were fire-scarred. Fire-scarred Douglas-fir stumps last longer than non-fire-scarred stumps owing to more resin deposition in the heartwood. It may be that Douglas-fir was somewhat more prevalent in the historical forest than what we found, but that evidence has since decayed. Fires after harvest also may have burned up stump evidence, although we attempted to control for this by deliberately avoiding areas where recent fires (within the past few decades) are known to have occurred. However, we assume for the purposes of 1860 stand reconstructions that the loss of stumps from any source has been minimal.

On the other hand, we are very confident in our ability to define living trees that established by 1860 using both size and morphological criteria (Figures 4 and 5). Less than 1% of the trees crossdated from subplots that we identified in the field as post-settlement established before 1860 (Figure 5), suggesting that we may have missed mapping only a very few currently living trees that were alive in 1860. Furthermore, age categories we assigned each tree in the field based on morphological characteristics matched very well with those derived from actual ages (Figure 4). Using a minimum tree size for assigning pre-settlement trees coupled with morphology categories allowed us to characterize age structure of living trees in the plots with relatively high confidence. Further sampling for age/size/morphology across the range of FRFRNet study areas will help further refine these relationships, which are especially crucial for retaining older trees in restoration treatment implementation.

4.3. Spatial stand structure

Similar to nonspatial structure, spatial arrangement of individual trees and groups in the 1860 forests also exhibited a great deal of diversity (Table 5; Figure 7). Diversity in tree clusters, singles trees, and openings have been found throughout the range of ponderosa pine where spatial patterning has been analyzed (Larson and Churchill 2012). In our study, a majority of trees in most plots were found in groups with other trees (Table 5). In spatially aggregated plots, 1860 era trees were typically found only in portions of a plot rather than scattered throughout (e.g., plots HA01 and HE22, Figure 7). We suspect that at least some of this aggregation was likely due to microsite variation related primarily to locally shallower or rockier soils. Although we did not explicitly map microsites within plots, notes and photographs taken in each suggest that some of the historical tree locations may be explainable by small-scale variations in topo-edaphic conditions. These areas were locations where surface fuels may have been reduced relative to surrounding deeper soils, and thus locations where likelihood of seedling survivorship during recurrent surface fires would have been higher. Other possibilities for tree aggregation may relate to differences in seedling survivorship in needle vs. grass fuelbeds. If a seedling established in a needle fuelbed below the canopy of an existing overstory, it may have had a better chance at surviving a fire than a seedling in the middle of a grassy meadow. For example, Abella et al. (2013) found strong variations in soil characteristics under openings vs. tree groups in historical forests of northern Arizona, and argued that local patterns within stands were largely self-reinforcing. Initial location of tree groups and openings may be the result of underlying topo-edaphic conditions but, once established, reinforced by variation in grass vs. needle fuelbeds and variation in fire intensities that allowed for greater chance of success for further seedling establishment. Historical spatial patterning of trees was undoubtedly the result of complex pattern-process interactions between soil and microsite characteristics, fire timing, fuelbeds, spatiotemporal variability in overstory mortality, seed caching by corvids and small mammals, and climate variation that created a diversity of tree spatial arrangements within stands and through time (e.g., Brown and Wu 2005, Larson and Churchill 2010, Churchill et al. 2013).

4.4. Implications for ecological restoration and treatment prescriptions

Spatiotemporal variability in fire timing and behavior before 1859 coupled with variation in climate regimes, landscape physiography, and other ecological processes resulted in high diversity in tree ages, sizes, and nonspatial and spatial structural metrics (Tables 3 and 5; Figures 2 and 6). However, after fire was removed from the ecosystem after 1859 and coupled with timber harvest, resulting stands are denser, contain greater basal areas, and are made up of smaller trees (Table 4). Such conditions have undoubtedly shifted fire behavior from largely surface fires to much more intensive and destructive crown fires, as has happened in recent fires in other locations across the frequent-fire zone of ponderosa pine forests in the northern Front Range (e.g., Graham 2003, FRFTP 2006, Graham et al. 2010).

Spatial and nonspatial structural data we reconstructed for the 1860 forest provide both justification and guidance for restoration of historical forest structure and fire regimes across Boulder County landscapes and similar ecosystems in the northern Front Range. Pre-settlement stand structures (e.g., Tables 3 and 5) are increasingly used as models for design of silvicultural treatments in ponderosa pine forests throughout its range (e.g., Fulé et al. 1997, Brown et al. 2008, Larson and Churchill 2012, Churchill et al. 2013, Reynolds et al. 2013). Silvicultural prescriptions across project areas should focus primarily on recreating stand- to landscape-scale variability with mosaics of individual trees, groups of trees of varying sizes, and openings, rather than focus on any central tendencies within individual metrics (Churchill et al. 2013, Reynolds et al. 2013). For example, many of the past fuel treatment prescriptions in this area were designed to reduce canopy continuity and fire hazard alone, and tended to focus solely on reducing tree densities and basal areas without consideration of spatial patterning. Past fuels treatments in the Boulder County study areas were largely “spacing-based” treatments, with relatively uniform residual tree densities and sizes and a lack of larger openings (e.g., >0.1 ha). However, fine-scale spatial patterning and diverse landscape structures are important factors for increasing resilience of ponderosa pine ecosystems (Churchill et al. 2013, Reynolds et al. 2013). Mosaics of tree groups, individuals, and openings affect patterns of burning, susceptibility to bark beetles, and tree recruitment and mortality (Churchill et al. 2013). Major goals of restoration treatments in the Boulder County landscapes should be both to restore elements of historical stand and landscape diversity as well as reducing tree density in any one stand or area.

However, once structural restoration objectives have been achieved in BCPOS areas, a major question for the future is what will be the role of fire across these landscapes. Ecological restoration is not a single event but a process, and a restoration focus that includes natural disturbance processes must be a consideration for continuing these forests into the future (Falk 2006). For example, stand and landscape structures will need to be maintained once they have been restored. In the past this was accomplished by relatively frequent surface fires that would kill a majority of tree regeneration before it has a chance to reach canopy status (Brown and Wu 2005). However, in locations such as the Boulder County Parks and Open Space lands, reintroduction of fire will prove difficult owing both to their proximity to private land and to considerations for smoke management above the major urban areas of the Colorado Front Range. However, it is not a question of if fire will ever again occur in these landscapes, but when it will occur and what kind of fire behavior will dominate. Wildfires may even be expected to increase in the future under projected warmer and drier conditions (e.g., Seager and Vecchi 2010, Rangwala et al. 2012). Restoration of forest structure should provide managers with a measure of “comfort” for reintroducing prescribed fires to these landscapes sometime in the future. However, over the long-term, managers – and more importantly, policy-makers and the general public – will also need to consider permitting managed wildfire use where naturally ignited fires are allowed to burn over selected areas under less extreme weather conditions. Smoke will still be a concern under these types of fire scenarios, but the alternative is wildfire that occurs under more extreme weather conditions and is much more destructive to forest resources, wildlife habitats, watersheds, and homes and other human infrastructure. Landscape-scale ecological restoration efforts will be critical to mitigate damaging effects from future wildfires in Front Range ponderosa pine forests and to maintain ponderosa pine ecosystems into the future.

Acknowledgements
For help in the field, we thank Brady Adams, Rob Addington, Baxter Brown, Josh Howie, Blaine Lemanski, Jason Martin, Jed Meunier, Nick Stremel, Chris Wanner, John Womack, Ben Wudtke, Boulder County Parks and Open Space staff members, City of Boulder staff members, and members of the Front Range Roundtable Science and Monitoring Team. This portion of the FRFRNet project was funded by Boulder County Parks and Open Space, Rocky Mountain Research Station, and Colorado Forest Restoration Institute at Colorado State University.

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Tables

Table 1. Plots sampled at Hall Ranch (HA) and Heil Valley Ranch (HE) Open Space study areas, arranged in order of descending elevation in each study area.

Plot	Elevation (m)	Aspect (deg)	Slope (%)	TRMI[3]	SI(m)[4]
HA24	2090	92	20	24	11.8
HA16	2008	60	21	43	12.5
HA05	1995	142	15	30	12.1
HA01	1986	270	18	29	11.6
HA17	1953	0	40	35	12.2
HA03	1907	180	40	22	8.0
HA18	1901	40	18	30	11.2
HE21	2092	72	18	36	15.7
HE19	2070	65	9	39	14.3
HE20	2036	340	36	31	12.5
HE13	1990	85	16	35	12.7
HE22	1960	80	12	32	10.8
HE18	1938	120	31	29	7.7
HE06	1905	260	26	27	11.8

[3] TRMI = Topographic relative moisture index (Parker 1982). Higher TRMI values indicate relatively more mesic sites than lower values.

[4] SI = Site Index base 100 years (Mogren 1956). Higher SI values indicate relatively more productive stands than lower values.

Table 2. Fire frequency (in years) from 1667 to 1859 for Heil Valley Ranch (HE) and Hall Ranch (HA) Open Space study areas. Fire frequencies are for fire years recorded only in HA or HE plots, for fire years recorded at either study area, and for fire years recorded in both study areas for the period of analysis.

Site	MFI (Std dev)[1]	MeFI[2]	WMPI[3]	WMode[4]	Range
Hall Ranch	14 (9)	12	12	9	3 to 36
Heil Valley Ranch	9 (6)	7	8	6	3 to 23
Combined either	8 (6)	4	7	4	2 to 20
Combined both	15 (10)	12	12	10	3 to 36

[1] Mean fire interval plus standard deviation

[2] Median fire interval

[3] Weibull distribution median probability interval (Grissino-Mayer 2001)

[4] Weibull distribution modal interval (Grissino-Mayer 2001)

Table 3. Plot structural metrics for all trees estimated to have been present in 1860 in plots at Hall Ranch (HA) and Heil Valley Ranch (HE) Open Space study areas. Structural metrics are: trees per hectare (TPH; trees ha^{-1}); tree basal area (BA; m^2 ha^{-1}), and stand quadratic mean diameter (QMD; cm).

Plot	TPH	BA	QMD
HA24	70	4.5	28.6
HA16	160	16.1	35.8
HA05	25	3.6	42.8
HA01	155	18.4	38.9
HA17	135	10.6	31.6
HA03	0	0.0	---
HA18	30	1.5	25.2
HE21	40	4.2	36.6
HE19	20	1.1	27.0
HE20	110	11.8	37.0
HE13	115	5.5	24.7
HE22	70	0.9	12.9
HE18	330	16.6	25.3
HE06	35	3.1	33.6
Minimum	0	0.0	12.9
25% quartile	31	1.9	25.3
Mean	93	7.0	30.8
75% quartile	130	11.5	36.6
Maximum	330	18.4	42.8

Table 4. Plot structural metrics for living trees ≥4 cm DBH at Hall Ranch (HA) and Heil Valley Ranch (HE) Open Space study areas. Structural metrics are: trees per hectare (TPH; trees ha^{-1}); tree basal area (BA; m^2 ha^{-1}), and stand quadratic mean diameter (QMD; cm).

Plot	TPH	BA	QMD
HA24	790	23.1	19.3
HA16	510	16.8	20.5
HA05	175	10.3	27.4
HA01	725	14.9	16.2
HA17	530	14.7	18.8
HA03	220	4.4	16.0
HA18	525	10.1	15.7
HE21	1010	22.1	16.7
HE19	350	21.8	28.2
HE20	825	22.0	18.4
HE13	680	18.6	18.7
HE22	635	15.3	17.5
HE18	515	19.7	22.1
HE06	615	20.4	20.6
Minimum	175	4.4	15.7
25% quartile	511	14.8	16.9
Mean	579	16.7	19.7
75% quartile	714	21.5	20.5
Maximum	1010	23.1	28.2

Table 5. Spatial metrics over 0.5 ha plots for trees present in 1860 in Hall Ranch (HA) and Heil Valley Ranch (HE) Open Space study areas. Distances in the Ripley's *L(d)* statistic indicate significant tree aggregation at those distances while random indicates that trees were distributed randomly across the 0.5 ha plot.

Plot	Proportion of trees in groups (%)	Modal group size (no. of trees)	Maximum group size (no. of trees)	Groups ha^{-1}	Ripley's *L(d)*(m)
HA24	41	2	5	8	8-18
HA16	65	2	14	18	4-18
HA05	0	--	--	0	Random
HA01	87	2, 8	11	18	6-18
HA17	81	2	10	24	1-10, 14-18
HA03	N/A	N/A	N/A	N/A	N/A
HA18	40	2	2	4	1-2
HE21	58	3, 4	4	4	2-18
HE19	0	--	--	0	Random
HE20	73	2	8	16	3, 8-12, 15-18
HE13	76	2	6	18	1-15
HE22	59	2, 8	8	4	3-18
HE18	91	2	24	60	Random
HE06	30	2	2	6	Random

Figures

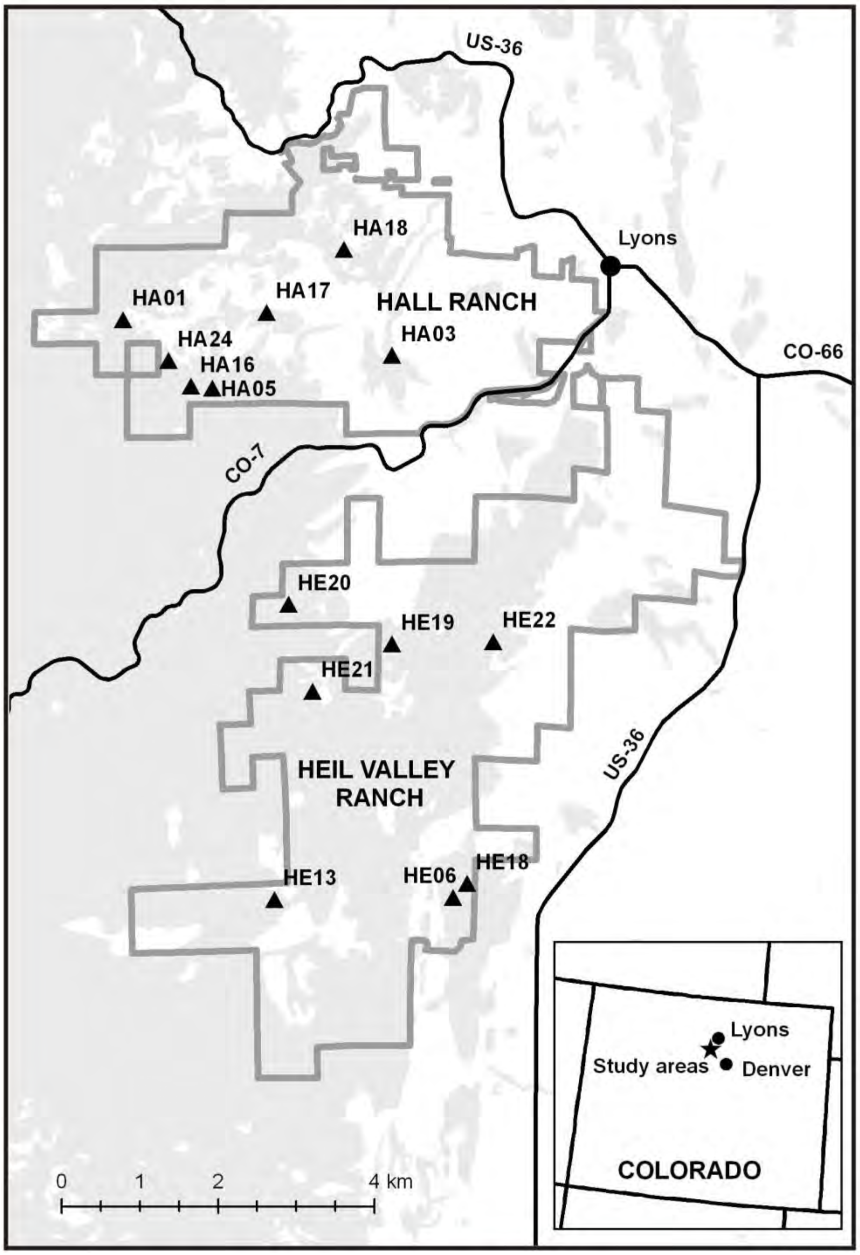

Figure 1. Locations of plots in the Hall Ranch (HA) and Heil Valley Ranch (HE) Open Space study areas. Grey shading represents distribution of current forest.

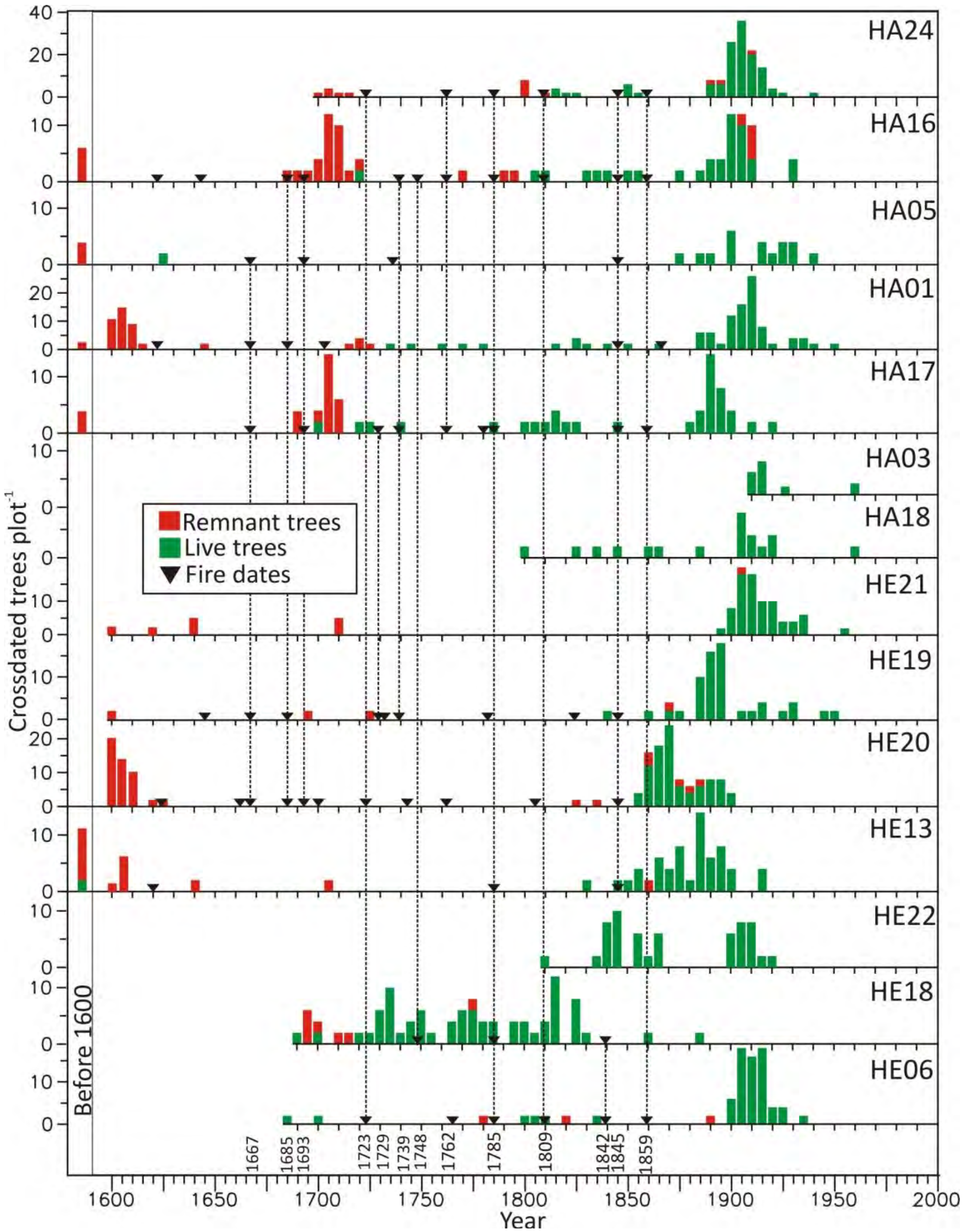

Figure 2. Fire and pith dates from crossdated trees sampled in HA and HE plots. Plots arranged by elevation in landscapes (as in Table 1). Tree pith dates for remnants (red bars) and living trees (green bars) are shown by 5-year periods for each plot with dates of fires represented by inverted triangles. Fire dates recorded by trees in ≥ 2 plots are indicated by vertical lines and labeled at the bottom of the graph. Histograms to the far left of the graph are pith dates of any trees that pre-date 1600 in a plot.

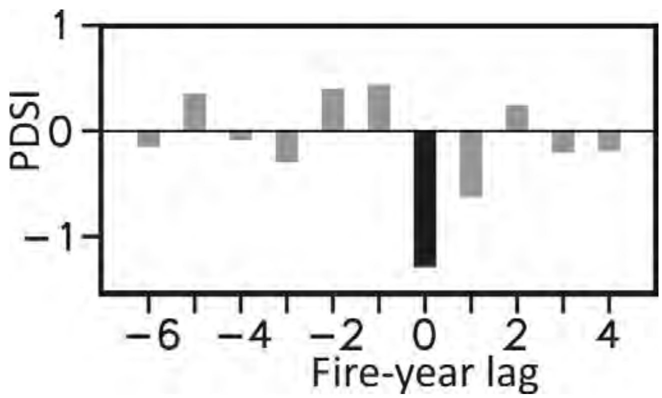

Figure 3. Superposed epoch analysis of fire dates recorded by trees in ≥ 2 plots (n = 13; dates at bottom of Figure 2) for the period of analysis from 1667 to 1859. Fire dates were tested against average summer Palmer Drought Severity Indices for northern Colorado (Cook et al. 2004). “0" year lag is average conditions for the fire years with pre- and post-fire years also tested. Black bar indicates significant ($p < 0.01$) drought conditions for tested fire years.

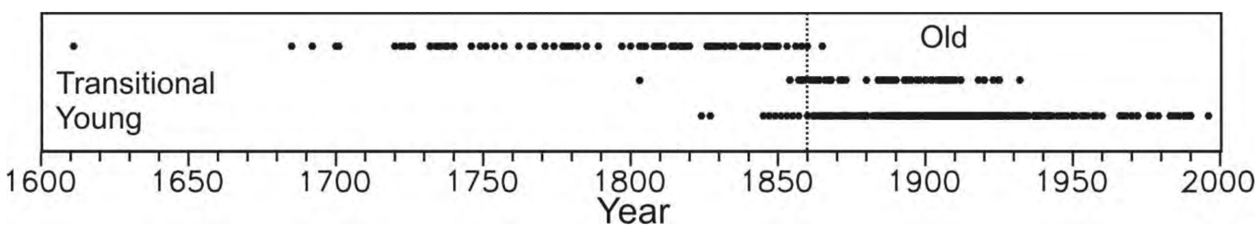

Figure 4. Pith dates on crossdated living trees classified in the field as old, transitional, or young based on tree morphology. Vertical dashed line is at 1860.

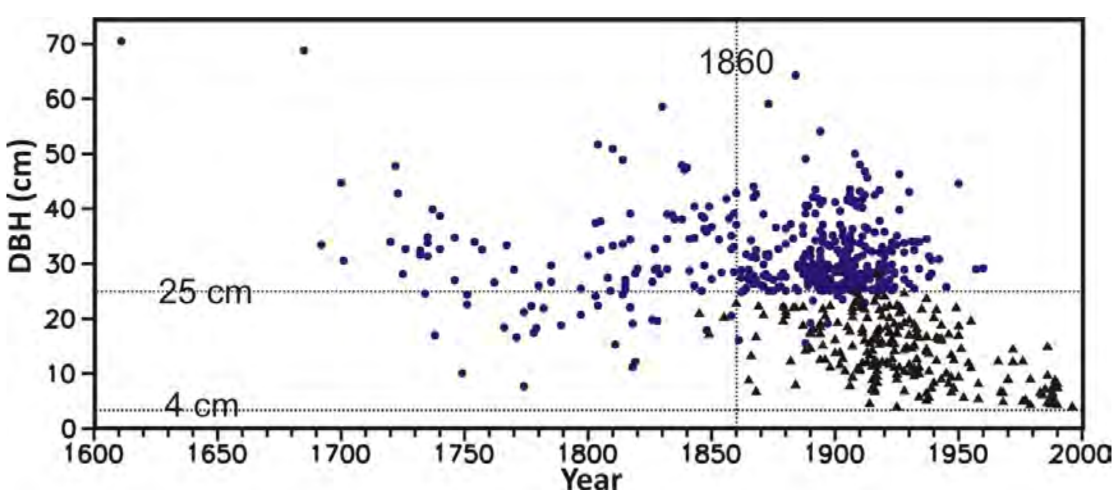

Figure 5. Pith dates and DBH of living pre-settlement (blue circles) and post-settlement trees (black triangles) sampled in subplots. Vertical dashed line is at 1860. Horizontal dashed lines are at 25 cm and 4 cm DBH, between which we sampled post-settlement trees.

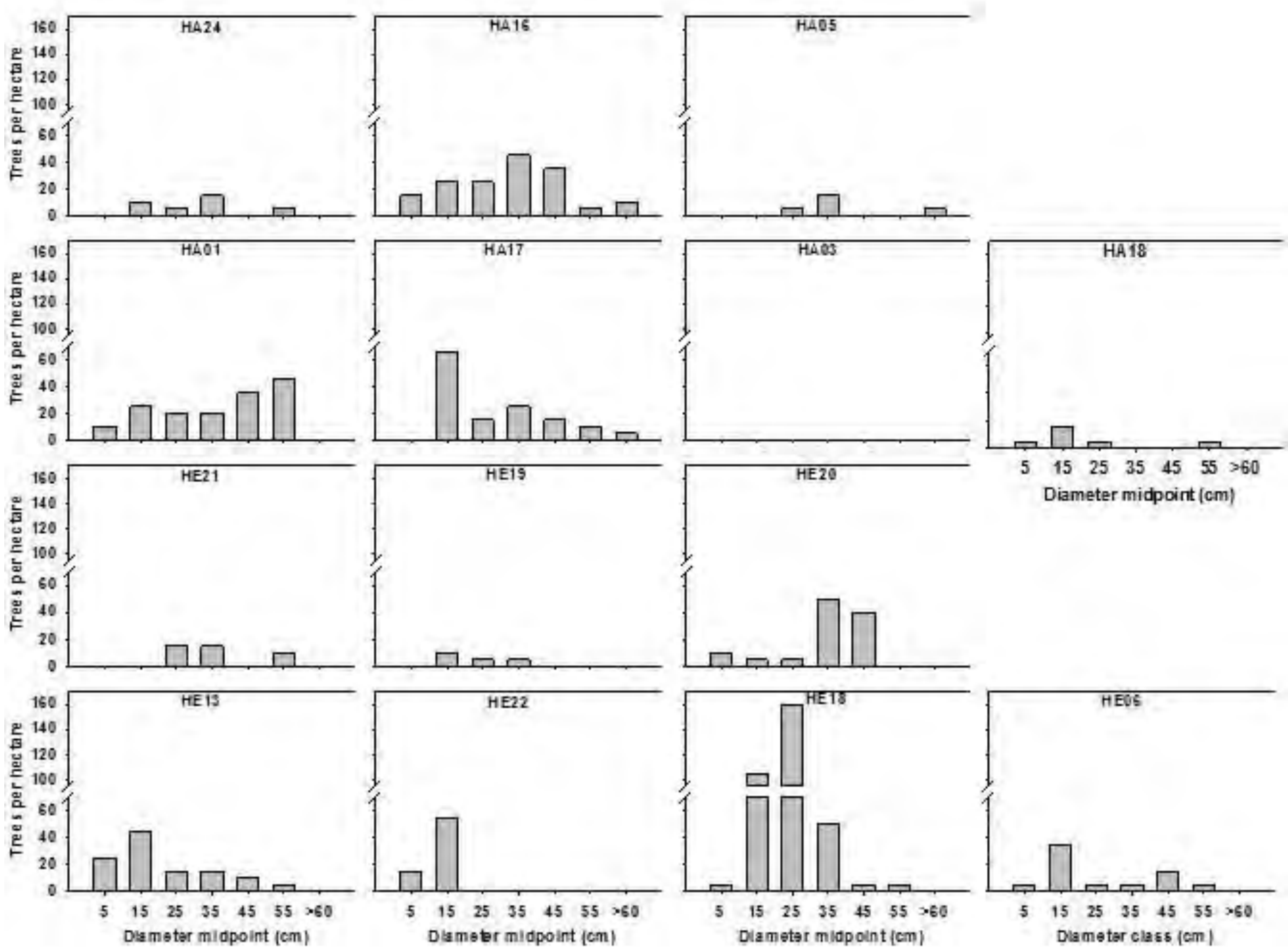

Figure 6. Historical (1860) diameter distributions by plot for Hall (HA) and Heil Valley (HE) Ranch study areas.

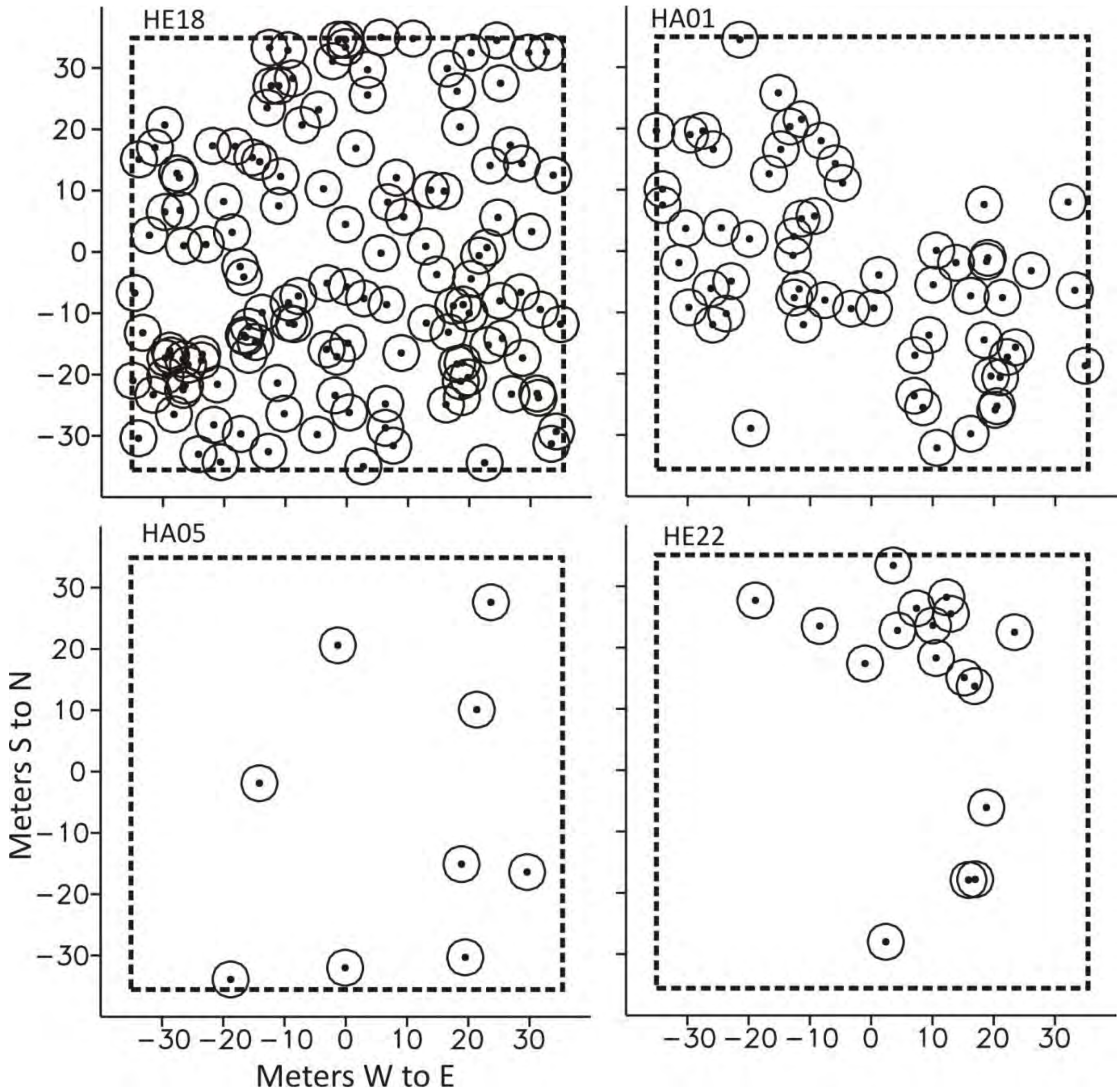

Figure 7. Stem maps of four HA and HE plots to show representative spatial forest structure. X,Y locations of tree stems are shown by closed circles with 6 m diameter crowns open circles. Left panels (HE18 and HA05) are plots where trees are randomly located while right panels (HA01 and HE22) exhibit significant tree clumping, according to Ripley's *L(d)* statistic (Table 5). Upper panels also represent denser stands and lower more open (Table 3).