Quantifying Forest Reference Conditions for Ecological Restoration: The Woolsey Plots

Final Report to the Ecological Restoration Institute for the Southwest Fire Initiative

March 2004

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Final Report to the Ecological Restoration Institute for the Southwest Fire Initiative

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Cover Design: "Peaks Through Pines" 2004 by **Andrew J. Sánchez Meador**

Executive List of Accomplishments

Project Title
Quantifying Forest Reference Conditions for Ecological Restoration: The "Woolsey" Plots

Investigators
Original PIs: Dr. Margaret M. Moore, Dr. W. Wallace Covington, Dr. Peter Z. Fulé, Dr. Pablo F. Parysow, Dr. David W. Huffman
Additional Investigators: Jonathan D. Bakker, Andrew J. Sánchez Meador, David M. Bell

Accomplishments

- Summary: Sixty-six of the approximately 140 original historical plots (or 47%) have been ***relocated*** on eight National Forests thus far. Of these 66 relocated plots – 0 (0/13) are spruce-fir, 13 (13/29) are mixed conifer, and the remainder 53 (53/98) are dominated by ponderosa pine (at least historically pine dominated). This study focused on the ponderosa pine-dominated plots, of which we have relocated over 54%. NOTE: This total does NOT include those historical plots located on the Long Valley Experimental Forest near Clint's Well, AZ.
- Total historical plots ***remeasured*** since 1997 is now 22 (22/98 or 22%); of these, 20 plots were stem-mapped (x,y locations of all trees ≥ 9.14 cm DBH) on four National Forests.
- Remeasurement (1.01 ha subplots) of six additional historical plots occurred during this project period (CIBS1B, COCS5B1, COCS5B2, COCS5C1, COCS5E2, PECS1A); Another subplot, COCS3A, was burned in 2000 and a new subplot was relocated within the larger plot.
- Five-year remeasurement of six 1.01 ha subplots was also completed during this period (CIBS1A, CIBS2A, COCS1A, COCS1B, COCS2A, COCS2B)
- Remeasurement and remapping of entire plot extent for four historical plots: COCS1A (2.6 ha), COCS5B1 (1.9 ha), COCS5B2 (1.2 ha), COCS5C1(1.2 ha); the full extent of COCS1B, COCS2A, COCS2B, COCS4A (3.2 ha), COCS4B (3.2 ha), COCS5A2 (1.2 ha), and COCS5B3 (1.2 ha) are scheduled to be mapped this summer (2004). Stem-mapped data over large areas such as these will be used to analyze spatial patterns for ponderosa pine on a variety of soil types.
- Remeasurement of three historical subplots that burned in wildfires of 2000: The subplots, located in Arizona (a portion of COCS3A and all of COCS3B subplot burned in the Pipe Fire) and New Mexico (JEMS2A burned in the Cerro Grande Fire); all three had been re-measured (1998-1999) before the wildfires occurred. All three plots were remeasured one-year (2001) post-burn; and again three years (2003) post-burn. Data are currently being analyzed for burn severity and recovery. Also, modified Whittaker plots were sampled on the burns in 2001; modified Whittaker plots on COCS3A and COCS3B were remeasured (and sample size increased) in 2003.
- Continued data entry of historical ledger data (1909 till late 1930s-1940s for all 21 plots); ledger data entry completed for all years for COCS1A; we continue to enter ledger data for other plots and dates.
- Continued analysis and development of forest overstory reconstruction model. Growth rates are being analyzed before and after initial harvest on plots.
- Data collection for model refinement includes: DBH vs. DGH (diameter at ground height) relationships; and decay rates (size data on dead material)
- Continued development of macro to visualize stands at different ages using known spatial coordinates of trees using the SVS computer program.

Accomplishments – con't.

- Data collection and initial analyses on permanent herbaceous understory plots includes remeasurement of 102 permanent herbaceous understory plots (each 1.5 x 3.0 m) established in 1914 on eight intensive overstory plots in Arizona. Mapped spatial locations of plants on 20 of these plots. Mapped spatial locations of herbaceous plants on 11 plots (each 1 x 1 m) on Woolsey plot COCS3B- recovery from burn. Located 48 of 60 understory plots (each 1 x 1 m) at 5 sites around Flagstaff (the 'Hill plots'); mapped spatial locations of plants on all plots.
- Entered ± 800 historical images into the Fort Valley Experimental Station collection on the Rocky Mountain Research Station (RMRS) image database; these images have been uploaded onto a USFS website (http://www.rmrs.nau.edu/imagedb/index.shtml) to be visited by managers and scientists interested in reference conditions and historical ecology.
- Archival searches (visited in person - to locate historical maps, photos, ledger data, etc.): Fort Valley Archives, RMRS, Flagstaff, AZ; Northern Arizona University Archives – Flagstaff; Museum of Northern Arizona, Flagstaff; University of Arizona Archives – Tucson, AZ; Arizona Historical Society – Tucson, AZ; Forest History Society, Durham, NC; NARA – Denver, CO; NARA – Beltsville, MD; NARA – Laguna Niguel, CA; and NARA – Ft Worth, TX (by phone).

Graduate Students

- Three outstanding graduate students were recruited between 2001- 2003 to work on portions of this project and extend the work over the next 2-4 years:
  - Jonathan Bakker (hired August 2001)
  - Andrew Sánchez Meador (hired January 2002)
  - David Bell (hired July 2003)

Proposals Written

- Six proposals were written during the period 2001-2003 to supplement and extend the work on this project (four proposals were funded):

  Moore, M. M. **"**Long-term vegetation change in a northern Arizona pine forest," 9/00; submitted to Mission Research Board, School of Forestry, Northern Arizona University; $95,000; initiated 1/02 – 12/05; extended to 2/06.

  Moore, M. M., P. Z. Fulé, P. F. Parysow, and D. W. Huffman. **"**Long-term and anticipated changes in southwestern conifer forests: Analysis and modeling of historical (1909-2001) permanent plot data," 11/15/01; submitted to USDA-NRI; $310,000; 12/02 – 12/06.

  Moore, M. M., and J. D. Bakker. "Evaluating plant demography in southwestern ponderosa pine-bunchgrass forests: Analysis of long-term chart quadrat data," 7/03; submitted to National Science Foundation; $275,314; 1/04 - 12/06**.** ***Not Funded.***

  Parysow, P. F., and M. M. Moore. "Are historical permanent plots representative of contemporary ponderosa pine populations in the Southwest?" 9/02; submitted to Mission Research Board, School of Forestry, Northern Arizona University; $28,000; 7/03-6/05.

  Parysow, P. "Generating and Sharing Essential Knowledge for Forest Restoration in the Southwest: Lessons from Old and New Permanent Plots," 7/03; submitted to National

Accomplishments – con't.

Science Foundation-CAREER Program; $549,002; 1/04 - 12/08***. Not Funded; Resubmitted 1/04.***

Parysow, P., and M. M. Moore. "Appraising Long-Term Permanent Plots in Southwestern Forests: Essential Information for Forest Restoration," 1/03; submitted to NAU Intramural Grant Program; $6,727; 7/03-6/04.

Presentations and Publications

· **Two** refereed manuscripts (one- *In press*, one – in preparation) and **seven** presentations (one-peer reviewed; two at National meetings) during the 2001-2003 period:

Bakker, J. D., and M. M. Moore. 2003. Historical ecology insights from long-term permanent plots: Understory vegetation on the Hill plots. Oral presentation at the 7th Biennial Colorado Plateau Conference, Flagstaff, AZ. November, 2003.

Bakker, J. D., and M. M. Moore. 2003. Long-term vegetation records on the Coconino National Forest. NAU Environmental Research Symposium, Flagstaff, AZ.

Bakker, J. D., and M. M. Moore. 2003. Long-term understory vegetation change in northern Arizona: the Woolsey and Hill plots. Forest Ecosystem Landscape Analysis meeting, Grand Canyon National Park, Flagstaff, AZ.

Bakker, J.D., M.M. Moore, J.D. Springer, and J.E. Crouse. 2002. Long-term (85-year) understory vegetation change in *Pinus ponderosa* stands of northern Arizona. Presentation at 87th Ecological Society of America and Society for Ecological Restoration Joint Conference, Tucson, AZ. August 2002.

Huffman, D.W., M.M. Moore, W.W. Covington, J.E. Crouse, and P.Z. Fulé. 2001. Ponderosa pine forest reconstruction: comparisons with historical data (peer-reviewed). Pp. 3-8 *in* Vance, G. K, C. B. Edminster, W. W. Covington, and J. A Blake (compilers), Ponderosa Pine Ecosystem Restoration and Conservation: Steps Toward Stewardship. Proc. USDA, Forest Service RMRS-P-22, Ogden, UT.

Moore, M. M., D. W. Huffman, P. Z. Fulé, W. W. Covington, and J. E. Crouse. 2004**.** Comparison of historical and contemporary forest structure and composition on permanent plots in southwestern ponderosa pine forests. *Forest Science* 50(2): ***In Press.***

Sánchez Meador, A. J., P. F. Parysow, and M. M. Moore. 2003. Forest stand reconstruction using historical permanent plots. Poster presentation at the 88th Annual Meeting of the Ecological Society of America, Savannah, GA. August, 2003.

Sánchez Meador, A. J, M. M. Moore, W. W. Covington, P. Z. Fulé, P. F. Parysow, D. W. Huffman, and J. D. Bakker. 2003. Quantifying forest reference conditions for ecological restoration: The Woolsey plots. Oral presentation at the Southwest Fire Initiative Conference, Flagstaff, AZ. April 2003.

Sánchez Meador, A.J., P. F. Parysow, and M. M. Moore. Reconstructing ponderosa pine forest patterns in northern Arizona using historically mapped permanent plots. ***Manuscript in preparation***, 2004.

Executive Summary

In this study, we relocated and remeasured a subset of the oldest known forest inventory plots in the American Southwest, established between 1909-1920s in Arizona and New Mexico. We used a combination of dendroecological and repeat forest inventory approaches to evaluate changes of forest structure and ecosystem function at decadal scales.

Sixty-six of the approximately 140 original historical plots (or 47%) have been ***relocated*** on eight National Forests thus far. Of these, 66 plots – 0 (0/13) are spruce-fir, 13 (13/29) are mixed conifer, and the remainder (53/98) are dominated by ponderosa pine; 31 plots are less than 0.2 ha (0.5 ac). This study focused on the ponderosa pine-dominated plots, of which we have relocated over 54%. Twenty-two plots (22%) were ***relocated and remeasured*** between 1997-2003 on four National Forests in Arizona and New Mexico. Fifteen of these 22 plots from both AZ and NM are our most complete data set to-date and were used to evaluate changes in forest structure and reconstruction techniques (Objectives 2, 3, 4). In addition, one plot (COCS1A) was used as a prototype to model structure temporally and examine indicators of ecosystem change (biomass, nutrients, fire susceptibility) (Objective 5) and quantify spatial patterns (Objective 6).

Tree structural remains are important in forest reconstruction to determine fire history and structural characteristics of past stand conditions (Fulé et al. 1997, Mast et al. 1999); or to determine the effects of partial cutting on tree composition and stand growth (Deal and Tappeiner 2002). The precision of these analyses is highly dependent on field identification of presettlement evidence, dendrochronological proficiency, and relationships utilized in "reverse" growth and decay modeling. We recognize former tree structures (e.g., snags, stumps, down logs, stump hole) in the field with a high degree of precision (Moore et al. 2004), however, a large source of error was linked to the imprecise reconstruction of tree diameters to their former size. In addition, overestimation of tree sizes, coupled with uncertainties about death/cut dates, lead to overestimates of past tree density in this study. We reduced these errors by using historical ledger accounts of death dates, but our reconstruction model still resulted in size overestimations.

Overstory structure on COCS1A has changed significantly between 1876 and 2002. A selective harvest in 1894 significantly reduced the stand density, total basal area (BA), and quadratic mean diameter. Since plot establishment in 1909, density and BA have increased to levels greatly exceeding those found in 1876. Canopy cover, overstory biomass, leaf area index, overstory nutrients, and forest floor depth are predicted to have increased as BA increased. Levels of all of these variables in 2002 exceeded the predicted levels in 1876. Understory production is predicted to have declined as BA increased, and was lower in 2002 than at any other date. In 2002, the overstory was dominated by small trees (< 20 cm DBH), many of which first grew to a height of 40 cm between 1900 and 1939. The crowning indices rose at harvest in 1894, and then decreased over time. Reduced crowning indices reflect higher potential to support an active crown fire, because the wind speed needed to carry a fire through the crown was lowered.

The spatial pattern differences between the historical (1909-reconstructed [as if harvesting had not occurred in 1894] and 1909-actual) and contemporary (2002) data sets on COCS1A were pronounced. Historically, this site exhibited dense clumps of trees averaging 0.02 ha in size alternating with sparsely populated interspaces between clumps. The partial harvest in 1894 homogenized the plot with respect to tree size by removing many of the largest diameter trees and changing the amount and distribution of tree sizes across the plot. At fine scales, the size of clumps was largely unaffected by harvesting; while at coarser scales, the clumpiness of the residual trees was increased because the harvest removed all of the trees in large patches. In 2002, the pattern was characterized by clumps that span large areas with few interspaces.

The tree harvests of the late 19th and early 20th century, together with fire exclusion, overgrazing, and climate change, altered the trajectory of stand development, ecosystem function, and spatial pattern of ponderosa pine stands in northern Arizona. Managers interested in reference conditions or restoration treatments should incorporate these historical factors in their decision making.

Project Title

Quantifying Forest Reference Conditions for Ecological Restoration: The "Woolsey" Plots

Introduction

Coniferous forest ecosystems of the Southwest have undergone dramatic changes in forest structure since Anglo-American and Hispanic settlement of the region , particularly in the ponderosa pine type (*Pinus ponderosa* Dougl. ex Laws. var. *scopulorum*) (Cooper 1960, Stein 1988, Covington and Moore 1994a, 1994b, Heinlein 1996, Fulé et al. 1997, Mast et al. 1999). Structural and functional changes in ponderosa pine and lower mixed conifer systems were driven by an irruption of pine and fire-intolerant tree species regeneration resulting from disruption of the frequent, low-intensity fire regime, livestock overgrazing, and high-grade logging (Pearson 1910, Arnold 1950, Cooper 1960, Stein 1988, Savage and Swetnam 1990, Savage 1991, Covington and Moore 1994b, Swetnam and Baisan 1996, Heinlein 1996). Ecologists and natural resource professionals generally agree that these changes have occurred and continue to occur throughout North America's frequent fire ecosystems; however, surprisingly little quantitative information is available about the magnitude and extent of these changes (Covington et al. 1994). Forest reconstruction techniques, which include dendroecological analysis of live and dead trees, suggest that tree densities on pine and pine-oak study sites in northern Arizona increased 2-7 times since EuroAmerican settlement (Covington and Moore 1994b, Fulé et al. 1997, Mast et al. 1999). Similar increases in tree numbers were reported for forests throughout the southwestern region (Johnson 1994).

In this study, we relocated and remeasured a subset of the oldest known forest inventory plots in the American Southwest, established from 1909-1920s in Arizona and New Mexico. We focused on those plots dominated by ponderosa pine. We used a combination of dendroecological and repeat forest inventory approaches to evaluate changes of forest structure and ecosystem function at decadal scales (Biondi 1999). Historical records in the USFS Rocky Mountain Station - Fort Valley archives allowed detailed comparisons between historical and present-day forest attributes. Information from historical, permanent plot research provides valuable data on forest dynamics prior to contemporary management practices and can help describe the natural range of forest structure (Minnich et al. 1995, Biondi 1996, Biondi 1999, Kipfmueller and Swetnam 2001). These data can, in turn, be used to evaluate ecological changes and guide management prescriptions (Kauffmann et al. 1994, Morgan et al. 1994, Landres et al. 1999, Moore et al. 1999, Kipfmueller and Swetnam 2001).

Objectives

Specific objectives of this research project were to:

1. Relocate permanent plots; remeasure a subset of ponderosa pine-dominated permanent plots established in the early 1900s so as to achieve an adequate sample size, and thus be able to analyze this unique data source.
2. Quantify forest structural (tree density, size, and age) and compositional differences on a subset (n=15) of permanent plots between the original plot establishment date (1909-1913) and our remeasurement date (1997 – 1999). These data were collected in 1997-99, but information was not published. Publication in a refereed journal was an objective of this study.
3. Reconstruct forest structure on a subset of plots at its establishment date (1909-1913) using dendrochronological techniques. Compare the reconstructed (modeled) and the historical (actual) forest structure for each plot to determine the precision, errors, and limitations of our reconstruction techniques and models.
4. Reconstruct forest structure at the date of fire exclusion (circa 1876-1890), showing forest structural conditions at the time of disruption of the long-term, frequent-fire regime (a.k.a.

presettlement). Compare species composition, tree densities and size distributions to 1909-1913 and contemporary conditions.
5. Use the Forest Vegetation Simulator (FVS; Teck et al. 1996) to determine and link stand structural changes with functional changes (tree biomass, carbon and nitrogen storage, herbaceous production, fire susceptibility, etc.) on ***one prototype*** plot (COCS1A) from the time of fire regime disruption (circa 1876) and initial plot establishment (1909) until the present.
6. Compare basic spatial pattern changes on ***one prototype*** plot (COCS1A) from initial plot establishment to present.

Background

In 1909, T.S. Woolsey, Jr., Assistant District Forester and Chief of the Office of Silviculture, District 3 (Southwestern District now Southwest Region 3), USFS; and G. A. Pearson, Director, Fort Valley Forest Experiment Station (Flagstaff, AZ), USFS, drafted a set of instructions that led to establishment of a network of permanent plots in ponderosa pine, mixed conifer, and spruce-fir forests of the Southwest (Pearson 1910, Woolsey 1911, Woolsey 1912). Between 1909 and the early 1920s (2 plots established in 1933, 1940, respectively), approximately 82 plots ranging in size from two to six hectares (ha) "intensive plots" to larger 32 ha "extensive plots" were established to evaluate stand growth, commercial potential, and natural regeneration of ponderosa pine, mixed conifer, and spruce-fir stands (Woolsey 1911, Pearson 1923, 1933). Approximately, 72% (59 of 82) of these plots were located in the ponderosa pine type of Arizona and New Mexico (Table 1.1).

An important criterion for plot establishment included location on areas where a timber sale had occurred within the last five years that followed current (early 1900) national forest harvest practices. Harvests may have been by a private timber company prior to or may have occurred simultaneously with plot establishment. In either case, the harvest must have followed the general practice in the national forests in which one-third of the merchantable volume was left, mainly in the form of immature trees (Pearson 1933). "So-called sample plots were established on logged over areas in order to ascertain how fast residual stands would grow, whether they could produce merchantable timber, and whether natural restocking would take place" (Pearson 1933, p. 272).

All live conifers ≥ 9.14 cm (3.6 in) diameter at breast height (DBH; 1.37 m or 4.5 ft) were measured and, for 20 plots, the spatial locations of all trees were recorded (stem-mapped). Data were recorded only for conifers that were commercially valuable in the early 1900s, although other species occurred on the site. Additional data recorded included species, age class, height, diameter, and condition class. Also, the location and diameter of standing dead trees, logs, and cut stumps were recorded on several plots.

General Methods

Study Area

The study area for this report included the network of 140 original permanent plots on the National Forests of Arizona and New Mexico (USFS Southwestern Region; now USFS Region 3). Between 1997 and 2002, we used historical descriptions of plot locations and searched these areas for original tree tags and monumented plot corners. Sixty-six of the approximately 140 original historical plots (or 47%) have been ***relocated*** on eight National Forests thus far. Of these 66 plots – 0 (0/13) are spruce-fir, 13 (13/29) are mixed conifer, and the remainder 53 (53/98) are dominated by ponderosa pine (or at least historically dominated). Thirty-one of the original 140 plots are less than 0.2 ha (0.5 ac) in size. This study focused on the ponderosa pine-dominated plots, of which we have relocated over 54%. **NOTE:** This total does NOT include those historical plots located on the Long Valley Experimental Forest near Clint's Well, AZ.

Out of the 53 pine-dominated plots we were able to relocate during this period, we selected a subset for remeasurement and detailed analysis. Criteria used for selecting the subset for analyses were: 1) historical stem map (tree locations) existed, 2) overstory trees were historically dominated by ponderosa pine (≥ 70% of the plot BA in the early 1900s), and 3) in cases of extreme disturbance (e.g., roads, urban development, etc.) that a minimally disturbed 1.01 ha subplot could be captured. We accepted plots that had received a precommercial or selective thin or light surface fire. We identified 21 plots that met ***all*** criteria thus far (including had stem map), and 22 plots have been remeasured to-date (Objective 1). General plot locations are located in Fig. 1.1 and Table 1.1. Fifteen of these 22 plots from both AZ and NM are our most complete data set to-date and were used to evaluate changes in forest structure and reconstruction techniques (Objectives 2, 3, 4). Descriptions and disturbance history of these 15 plots are listed in Table 1.2. The Arizona plots (COC prefix) examined in this study fall within the Colorado Plateau physiographic region, while the New Mexico plots fall within two physiographic regions, the southern tip of Southern Rocky Mountains (JEM plots), and Basin and Range (GILA). The CIB plots, located southwest of Magdelena, NM, lie in an interesting transition zone between the Colorado Plateau to the north and the Basin and Range to the south (Chronic 1987). The plots examined in detail for this study represented six ponderosa pine habitat types of the Southwest (Moir 2000).

Field Measurements

We used survey and forest inventory methods originally employed at plot establishment in the early 1900s. Historical stem maps were used to reestablish the original plot layout of continuous 1 chain by 1 chain quadrats (0.04 ha or 0.10-ac; Fig.1.2). Most of the original plot corners and many of the interior markers were evident and aided in plot reestablishment. In order to achieve our secondary objective without bias, the historical maps were not consulted again until contemporary measurements were completed. This allowed us to test our ability to locate and identify structural evidence of the former stand after 80+ years of change.

The original plots examined for this study were “intensive” plots; therefore, they ranged in size from 2.0 to 6.1 ha in size. We standardized remeasurement by delineating one 1.01-ha (2.5 ac) subplot within each historical plot. Each subplot was subdivided into 25 grid cells, each cell was one square chain (20.1 x 20.1 m; 0.10 acre; or 66 ft on the side), which duplicated the original plot layout and facilitated remeasurement. The 1.01 ha subplot will hereafter be referred to as “plot”. An area of 1.01 ha: 1) ensured that presettlement ponderosa pine tree groups (0.1 to 0.3 ha in size; White 1985) were captured in the data, 2) reduced edge effect thereby minimizing problems of comparisons with the historically mapped data, and 3) allowed remeasurement of a relatively large unit within time and funding constraints. For consistency, the northwest corner of the original plot was randomly selected as the origin for establishment of each contemporary plot. If this corner was disturbed, then alternate origins were selected by progressing clockwise to successive corners of the same plot.

Grid cells within each 1.01 ha plot were searched and all evidence of living or dead tree structures, either presently or at some past time reaching at least 1.37 m height, were numbered and tagged. Structures included live trees, snags, logs, stumps, and stump holes. Species, DBH, and condition class (1-9; see below) were recorded for all structures. Diameters were measured at DBH to the nearest tenth of an inch with a diameter tape and then converted to metric units. If the original tree tag still existed, however, we measured diameter at the nail and tag.

Trees were cored at 40 cm above ground level to determine tree age. Ponderosa pine, Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), white fir (*Abies concolor* Gord. & Glend.), limber pine (*Pinus flexilis* James), or southwestern white pine (*Pinus strobiformis* Engelm.) with DBH ≥ 37 cm or ponderosa pine of any size with yellowed bark (White 1985, Mast et al. 1999) were considered potentially presettlement trees or at least established at the time of original plot establishment. All living potentially presettlement or original plot establishment trees were cored for determination of age and past size. Trees that established after the original plot establishment date were randomly sampled at a sampling rate that averaged 20%.

Tree condition classes followed a classification system commonly used in ponderosa pine forests (Maser et al. 1979, Thomas et al. 1979). The nine classes were: 1) live, 2) fading, 3) recently dead, 4) loose bark snag, 5) clean snag, 6) snag broken above breast height, 7) snag broken below breast height, 8) dead and down, 9) cut stump, and 10) stump hole (class added in 2000).

The spatial location of each tree was measured using a criterion laser.

Definitions

To make the best comparisons possible with the historical data, tree structures were classified into broad age classes (Table 1.3). We used the descriptions provided by White (1985) to classify trees as postsettlement and presettlement in origin. These classifications were thought to correspond well with Woolsey's (1911) description of trees as "blackjack" and "yellow pine", respectively. Woolsey (1911; p. 5-6) wrote, "Blackjack is merely the form which yellow pine assumes before it reaches 125 or 150 years, during which period its bark is dark red-brown or blackish, with narrow furrows, in strong contrast to the lighter, widely furrowed bark of mature trees".

Location of Historically Measured Trees

When remeasurement was completed, we used the original maps to systematically visit the location of each historically measured tree and evaluate our success in locating these same trees after 80 - 90 years. We identified historically measured trees on the basis of their mapped locations in conjunction with the bark characteristics, sizes of trees, and presence of historical tree tags. Historically measured trees that were missed during remeasurement were recorded and notes were made regarding tree attributes (historical and current) or condition classes (e.g., live, dead and down, no evidence). Hereafter, these trees are labeled "missing".

Analyses and Results

NOTE: **Analyses, results and discussion are described separately for each study objective below. More specific methods are also added to each objective when necessary.**

<u>Objective 1</u>: Relocate permanent plots; remeasure a subset of the permanent plots so as to achieve an adequate sample size

Analyses: no specific analysis for this objective.

Results and Discussion*:* Sixty-six of the approximately 140 original historical plots (or 47%) have been ***relocated*** on eight National Forests thus far. Of these 66 plots – 0 (0/13) are spruce-fir, 13 (13/29) are mixed conifer, and the remainder 53 (53/98) are dominated by ponderosa pine (or at least historically dominated). This study focused on the ponderosa pine-dominated plots, of which we have relocated over 54%.

Of these ponderosa pine plots, 30% (29/98) are located in a cluster approximately 35 km southwest of Flagstaff, AZ (known as the COCS5 or Coulter Ranch plots; Table 1.1). In addition, thirty-one of the original 140 plots are less than 0.2 ha (0.5 ac) in size (99% are ponderosa pine) (Table 1.1); we have not and probably will not focus much attention on these small plots.

Twenty-two ponderosa pine-dominated plots were ***relocated and remeasured*** (22/98 or 22%) between 1997-2002 on four National Forests in Arizona and New Mexico; of these, twenty plots were stem-mapped. Five-year remeasurements have occurred on six plots (originally relocated and measured in 1997-1998; and remeasured in 2002-2003). Three plots remeasured in 1998 were burned in wildfires in 2000 so we collected 1- and 3-year post-burn measurements to track individual tree response to crown fire. Fifteen of these 22 plots are our most complete data set to-date; and this complete set was used to evaluate changes in forest structure and reconstruction techniques (see objectives 2, 3, 4) for this study. In addition, one plot (COCS1A) was used as a prototype to model structure temporally and to examine indicators of ecosystem change (biomass, selected nutrients, fire susceptibility, etc.) (see objective 5) and to quantify spatial patterns (see objective 6).

<u>Objective 2</u>: Structural and compositional changes on 15 plots in AZ and NM

Woolsey plot data were collected from 1997-1999 on 15 plots in Arizona and New Mexico as part of a project funded by the USFS Rocky Mountain Research Station - Research Joint Venture (JV) Agreement 28-JV7-939. Data collection and preliminary analyses were reported as part of a USFS JV agreement (Moore et al. 2000). Error correction, final data analyses, and manuscript publication (Moore et al. 2004) were part of the deliverables for this study and final report. Please see abstract below. A reprint of the manuscript will be forwarded to the Ecological Restoration Institute when it arrives in April, 2004.

Moore, M. M., D. W. Huffman, P. Z. Fulé, W. W. Covington, and J. E. Crouse. 2004. Comparison of historical and contemporary forest structure and composition on permanent plots in southwestern ponderosa pine forests. Forest Science 50(2): ***In Press.***

Abstract. We compared historical (1909-1913) and contemporary (1997-1999) forest structure and composition on 15 permanent plots in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests of Arizona and New Mexico. We used the same sampling methods as in the early 1900s and compared stand density, diameter distributions, species composition, and broad age-classes from the two periods. Stand density (trees ≥ 9.14 cm DBH) significantly ($p < 0.001$) increased on plots from an average of 77.4 trees per plot (s = 49.9) at plot establishment in 1909-1913 to 519.1 trees per plot (s = 252.3) at remeasurement in 1997-1999. Basal area significantly ($p < 0.001$) increased from 8.0 m^2 per plot (s = 3.5) to 28.5 m^2 per plot (s = 10.1). Contemporary tree diameter distribution shifted towards smaller size classes as demonstrated by a significant ($p = 0.001$) decrease in quadratic mean diameter from 38.5 cm (s = 7.5) in 1909-1913 to 28.6 cm (s = 7.1) in 1997-1999. Broad age-classes yielded an average of 61.5 (s = 49.5) residual live trees classified as "blackjack" ponderosa pine (*P. ponderosa* < 150 yrs) and 13.3 (s = 11.9) "yellow pine" (*P. ponderosa* ≥ 150 yrs) in 1909-1913. In 1997-1999, 416 live trees (s = 229.6) were "blackjack" and 57.2 (s = 28.5) trees on average were "yellow pine". Twelve of the 15 plots were not invaded by other tree species (remained pure ponderosa pine type), while composition shifted slightly on three plots towards more shade-tolerant and fire-intolerant species. Ninety-one percent of the historically (1909-1913 or older) mapped tree structures (live trees, snags, logs, stumps, etc.) were relocated, which suggested that the forest reconstruction field techniques are reliable within 10%. Dramatic increases in tree densities may represent an increased potential for bark beetle epidemics and stand replacing wildfire over large areas in the Southwest.

Key Words: *Pinus ponderosa*, forest structural changes, residual stands, early 1900s, reference conditions, T. S. Woolsey, Jr., G. A. Pearson, Arizona, New Mexico

List of Figures for General Methods and Objectives 1 and 2.

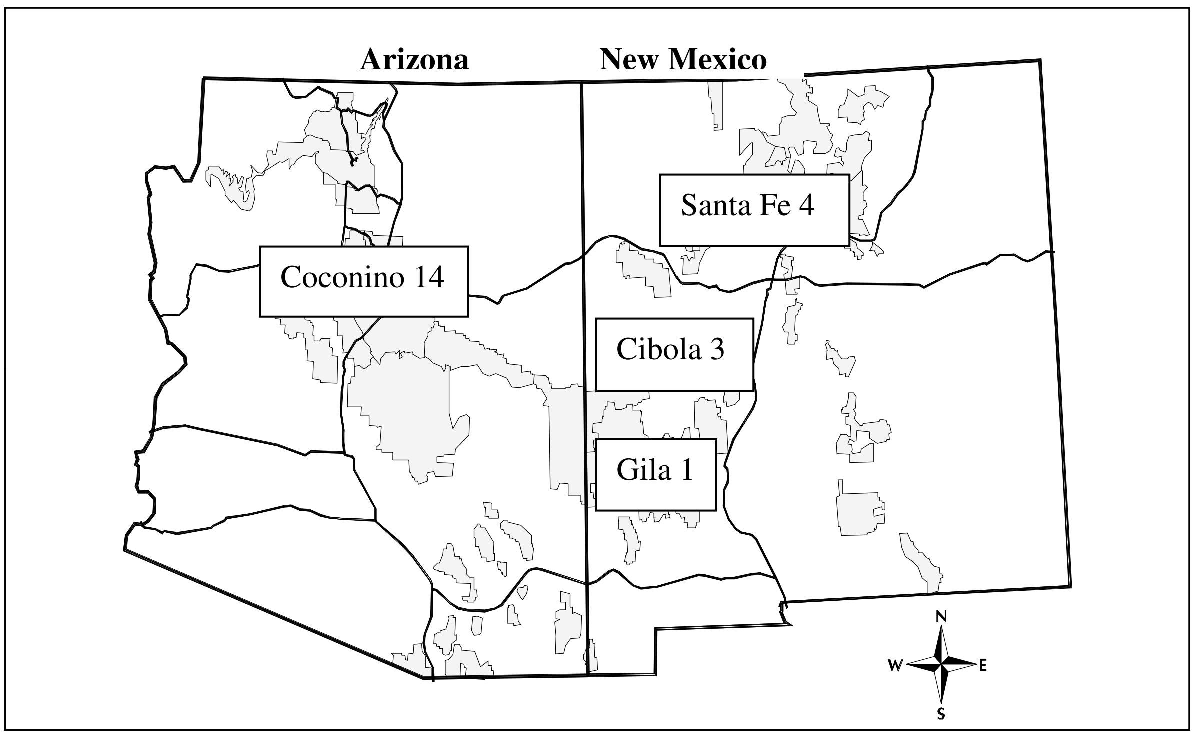


Fig. 1.1

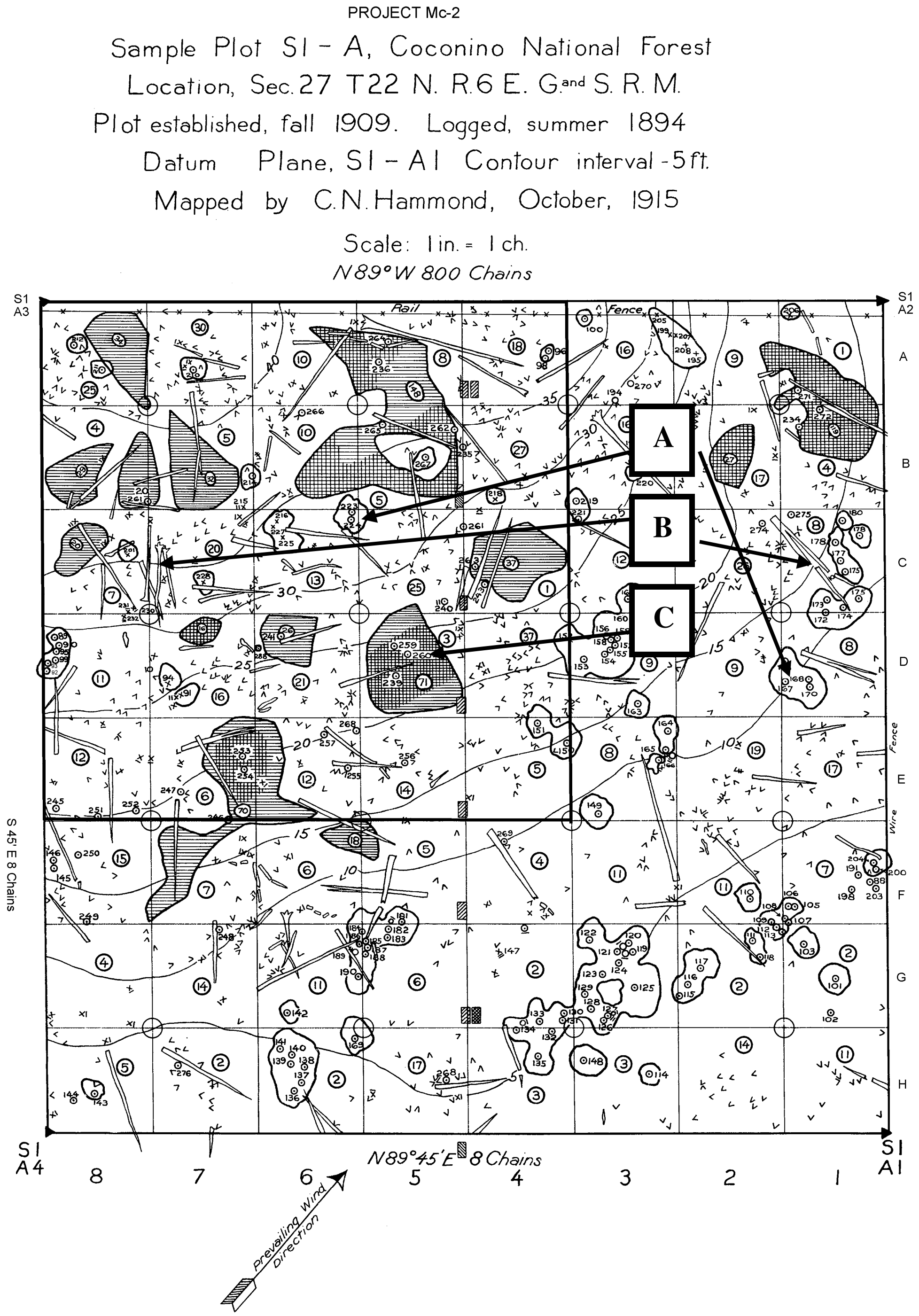

PROJECT Mc-2
Sample Plot S1 - A, Coconino National Forest
Location, Sec. 27 T22 N. R.6 E. G.and S. R. M.
Plot established, fall 1909. Logged, summer 1894
Datum Plane, S1 - A1 Contour interval - 5 ft.
Mapped by C.N. Hammond, October, 1915
Scale: 1 in. = 1 ch.
N89°W 800 Chains
S1 A3
S1 A2
S1 A4
S1 A1
Rail
Fence
Wire Fence
A
B
C
S 45' E 8 Chains
N 1°45' W 8.00 Chains
N89°45'E 8 Chains
8
7
6
5
4
3
2
1
Prevailing Wind Direction

Fig. 1.2

Table 1.1. Details of historical plots in Arizona and New Mexico established by T. Woolsey and G. Pearson (data from USFS Ft. Valley Archives, Flagstaff, AZ)

National Forest	Plot (No.)	Size (ac)	Date of Origin	Info. and data that exists and has been located				Date Relocated	Plot Condition	Section, Township and Range	Elevation (ft)	Stand Type
				Location Map	Stem Map	Ledger Data	Photos					
Apache-Sitgreaves	Conklin-1	1.6	1910							Sec 6 & 7, T5N, R28E		MC
	Conklin-2 (S1)	1.2	1910	√	√	√(1916)		**		Sec 6 & 7, T5N, R28E	9,150	MC
	Conklin-3 (S2)	2.0	1910	√	√	√(1916)		1997	intact	Sec 6 & 7, T5N, R28E	9,110	MC
	Conklin-4	1.6	1910							Sec 7, T5N, R28E		MC
	Conklin-5	1.6	1910							Sec 7 & 8, T5N, R28E		MC
	CC Flat-1	1.2	1911							Sec 32,T9N, R26E		MC
	CC Flat-2 (S3)	1.2	1911	√	√	√(1916)		2001		Sec 32,T9N, R26E	9,200	MC
	CC Flat-3	2.5	1911							Sec 32,T9N, R26E		MC
	Decker Wash- 1A-1D (4)	0.1	1926							T12N, R18E	7,000	PP
	Decker Wash - 1E	0.1	1926							T12N, R18E	7,000	PP
Coconino	**Ft Valley-S1A**	6.4	1909	√	√	√(1949)	√	1997	intact	Sec 27, T22N, R6E	7,300	PP
	Ft Valley-S1B	10.0	1909	√	√	√(1949)	**	1997	intact	Sec 27, T22N, R6E	7,300	PP
	Ft Valley-S2A	7.0	1909	√(description)	√	√(1949)	√	1997	intact	Sec 25, T22N, R6E	7,300	PP
	Ft Valley-S2B	4.9	1909	√	√	√(1949)	√	1997	mostly intact	Sec 25, T22N, R6E	7,300	PP
	Wing Mt.-S3A	12.0	1909	√	√	√(1959)	√	1997	disturbed	Sec 24, T22N, R5E	7,400	PP
	Wing Mt.-S3B	12.0	1909	√	√	√(1959)	√	1997	destroyed	Sec 24, T22N,R5E	7400	PP
	Doney Park-S4A	8.0	1909	√ (description)	√	√(1949)	**	1997	intact	Sec 22, T22N, R8E	6,700-6.875	PP
	Doney Park-S4B	8.0	1909	√	√	√(1949)	**	1997	intact	Sec 22, T22N, R8E	6,700-6.875	PP
	Coulter Ranch-S5A1	4.8	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5A2	3.0	1913	√	√	√(1933)	√	2003	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5A3	1.8	1913	√	√	√(1933)		1999	intact	Sec 24 & 23, T19N, R7E	6,500	PP
	Coulter Ranch-S5A4	1.8	1913	√	√	√(1933)		1999	intact	Sec 30, T19N, R8E	6,500	PP
	Coulter Ranch-S5B1	4.8	1913	√	√	√(1933)	√	2003	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5B2	3.0	1913	√	√	√(1933)	√	2003	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5B3	3.0	1913	√	√	√(1933)	√	2003	intact	Sec 24 & 23, T19N, R7E	6,500	PP
	Coulter Ranch-S5B4	1.8	1913	√	√	√(1933)		1999	intact	Sec 25, T19N, R7E	6,500	PP
	Coulter Ranch-S5C1	3.0	1913	√	√	√(1933)	√	2003	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5C2	2.4	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5C3	1.8	1913	√	√	√(1933)		1999	intact	Sec 24 & 23, T19N, R7E	6,500	PP
	Coulter Ranch-S5C4	1.8	1913	√	√	√(1933)		1999	intact	Sec 25, T19N, R7E	6,500	PP
	Coulter Ranch-S5D1	2.0	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5D2	2.0	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5D3	2.0	1913	√	√	√(1933)		1999	intact	Sec 24 & 23, T19N, R7E	6,500	PP
	Coulter Ranch-S5D4	1.8	1913	√	√	√(1933)		1999	intact	Sec 25, T19N, R7E	6,500	PP
	Coulter Ranch-S5E1	2.0	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5E2	2.5	1913	√	√	√(1933)	√	2003	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5E3	2.0	1913	√	√	√(1933)		1999	intact	Sec 24 & 23, T19N, R7E	6,500	PP
	Coulter Ranch-S5E4	1.8	1913	√	√	√(1933)		1999	intact	Sec 25, T19N, R7E	6,500	PP
	Coulter Ranch-S5F1	2.0	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5F2	2.0	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5F3	2.0	1913	√	√	√(1933)		1999	intact	Sec 24 & 23, T19N, R7E	6,500	PP
	Coulter Ranch-S5F4	0.8	1913	√	√	√(1933)		1999	intact	Sec 30, T19N, R8E	6,500	PP
	Coulter Ranch-S5G1	2.0	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5G2	2.0	1913	√	√	√(1933)		1999	intact	Sec 24, T19N, R7E	6,500	PP
	Coulter Ranch-S5G3	2.0	1913	√	√	√(1933)		1999	intact	Sec 24 & 23, T19N, R7E	6,500	PP
	Coulter Ranch-S5G4	0.8	1913	√	√	√(1933)		1999	intact	Sec 25, T19N, R7E	6,500	PP
	Coulter Ranch-S5H4	0.8	1913	√	√	√(1933)		1999	intact	Sec 25, T19N, R7E	6,501	PP
	GPNA-S6A	76.0	1915	√	*	√(1955)		***	intact	Sec 22, T22N, R6E	7,400	PP
	S6B	73.9	1940	√	*	√(1976)	√	***	intact	Sec 22, T22N, R6E	7,400	PP
	S7	160.0	1925					***		Sec 22, T22N, R6E	7,500	PP
	Schoolhouse Plot-S8	8.0	1926	√	*	√(1946)	√	***		T20N, R7E		PP
	S9	80.0	1941					***		Sec 22, T22N, R6E	7400	PP
	Tusyan Series 1 (3)	0.05-0.1	1924					***				PP
	Hart Prairie- 2A-2H (8)	0.08-.2	1926-27					***		Sec 22, 15, & 16 T22N, R6E	7,700	PP
Prescott	Copper Basin (3)	0.6	1933	√	**	√(1948)		2002	destroyed	Sec 13, T13N, R2W	6,400	PP
	White Spar-A	4.2	1925	√		√(1945)		2003	mostly intact	Sec 20, T13N, R2W	5,800	PP
	White Spar-B	0.8	1925	√		√(1945)		2003	intact	Sec 20, T13N, R2W	5,800	PP
	White Spar-C	1.2	1925	√		√(1945)		2003	mostly intact	Sec 20, T13N, R2W	5,800	PP
	White Spar-D	0.2	1930	√		√(1945)		2003	intact	Sec 20, T13N, R2W	5,800	PP

Total: 70

National Forest	Plot (No.)	Size (ac)	Date of Origin	Info. and data that exists and has been located: Location Map	Stem Map	Ledger Data	Photos	Date Relocated	Plot Condition	Section, Township and Range	Elevation (ft)	Stand Type
Carson	Amola-S3	2.9	1914	√	**		√	2003	intact	Sec 36, T23N, R12E	6,800	PP
	Gallegos-S4	?	1914	√				***		Sec 3, T22N, R13E		MC
	Cienega-S5	4.0	1915		**			2003	disturbed	Sec 25, T23N, R12E		PP
	Osha Canyon-S6	2.5	1914	√				***		Sec 6, T22N, R13E		PP
	Rio Pueblo-S9	4.2	1915	√	**			**		Sec 6, T22N, R16E		MC
	La Junta-S7	2.8	1915	√	**			1997	intact	Sec 20, T22N, R14E		MC
	Angostura-S1	1.0	1922	√	√			***		Sec 7, T21N, R14E	10,000	ES
	Angostura-S2	1.0	1922	√	√			***		Sec 13, T21N, R13E	10,300	ES
	Angostura-S3	2.0	1922	√	√			***		Sec 11, T21N, R13E	10,300	ES
	Angostura-S4A	2.0	1922	√	√			***		Sec 13, T21N, R13E	11,000	ES
	Angostura-S4B	1.0	1927	√				***		Sec 13, T21N, R13E	11,000	ES
	Angostura-S5	32.9	1922	√	√			***		See Woolsey Binder	10,000-11,500	ES
	Angostura-S6	1.0	1924	√				***		Sec 18, T21N, R14E		ES
	Angostura-S7	0.5	1924	√				***		Not in book		ES
	Angostura-S8	1.0	1924	√				***		Sec 11, T21N, R13E		ES
	Angostura-S9	5.5	1924	√				***		Sec 13, T21N, R13E		ES
	Angostura-S10	0.5	1924	√				***		Sec 11, T21N, R13E		ES
	Tres Piedras	?	1922	√				***		Sec 34, T28N, R9E	9,000	PP
	Pinebetal	?	1922	√				***		Sec 19, T31N, R8E	9,000	PP
	H&H Sale (6)	2.0-3.5	1914	√				***		See Woolsey Binder		PP/MC
	Sundling (2)	?	1924					***		Not In Binder	10,300	ES
Gila	**Mogollon-S1A**	6.0	1912	√	√	√(1939)	√	1997	mostly intact	Sec 4 T11S, R18W	9,200	PP
	Pintos Altos-S2A	6.4	1912	√	√	√(1939)	√	**	disturbed	Sec 31, T15S, R13W	7,300	PP
	Redstone (16)	0.1-0.3	1933	√				***		See Woolsey Book	7,300	PP
Cibola	**S1A**	6.0	1910	√	√	√(1935)		1997	mostly intact	Sec 11, T5S, R7W	8,300	PP
	S1B	6.0	1910	√	√	√(1935)		1997	intact	Sec 11, T5S, R7W	8,300	PP
	S2A	14.4	1910	√	√	√(1935)		1997	intact	Sec 9, T5S, R7W	8,200	PP
Lincoln	Reserve 1	10.0	1937	√				***		Sec 5, T16S, R12E	8,600	DF
	Reserve 2	5.0	1937	√				***		Sec 5, T16S, R12E	8,600	DF
	Reserve 3	2.5	1937	√				***		Sec 5, T16S, R12E	8,600	DF
	Reserve 4	2.5	1937	√				***		Sec 5, T16S, R12E	8,600	DF
	Cox Canyon-S1	10.0	1925	√				**		Sec 16, T16S, R12E	8,600-9,000	MC
	Cox Canyon-S2	1.6	1925	√				**		Sec 16, T16S, R12E	8,600-9,000	MC
	Cox Canyon-S3	8.0	1925	√				**		Sec 16, T16S, R12E	8,600-9,000	MC
	Cox Canyon-S4	5.0	1925	√				**		Sec 16, T16S, R12E	8,600-9,000	MC
	Cox Canyon-S5	5.0	1925	√				**		Sec 16, T16S, R12E	8,600-9,000	MC
	Cox Canyon-S6	2.0	1925	√				**		Sec 16, T16S, R12E	8,600-9,000	MC
	Cox Canyon-S7	3.0	1925	√				**		Sec 36, T15S, R12E	8,600-9,000	MC
	Cox Canyon-S8	2.0	1925	√				**		Sec 36, T15S, R12E	8,600-9,000	MC
	Cox Canyon-S9	2.0	1927	√				**		Sec 16, T16S, R12E	8,600-9,000	MC
	Douglas-Fir Pruning (2)	1.0	1939					***		Sec 16, T16S, R12E	9,000	DF/MC
Santa Fe	**Pecos S1A**	6.0	1911	√	*	√(1934)		2001	intact	Sec 34, T17N, R14E	7,800	PP
	Pecos S2A	6.0	1911	√	√	√(1934)		1999	intact	Sec 34, T17N, R14E	7,500	MC
	Willow Creek S4A	4.0	1929	√	√	√(1934)		**		Sec 24,T18N, R12E	8,600	DF
	Willow Creek S4B	0.2	1929	√				***		Sec 24,T18N, R12E	8,600	DF
	Jemez S1A	6.0	1911	√	√	√(1934)		1997	destroyed	Sec 8, T19N, R6E	7,500	PP
	Jemez S2A	6.0	1911	√	√	√(1934)		1997	disturbed	Sec 22,T19N, R6E	6,800	PP
	Jemez S3A	6.0	1911	√	√	√(1934)		1997	mostly intact	See Woolsey Binder	8,200	PP
	Total: 70											

List of Abbreviations:

√ indicates the information or data that have been located (i.e., either from a Forest Service or National Archive Location).
* may not have ever existed (from looking at records of original data).
** an attempt was made to locate these plots or data, but as of 1/23/03, they have not been found.
*** not visited as of 1/23/03.
Dates in the re-measure column indicate the last date data were collected.
Bolded sites indicate sites from which remeasurement data has been collected.`

Stand Type Code:

PP = Ponderosa pine
DF = Douglas-fir
MC = Mixed conifer species
ES = Engelmann spruce

Table 1.2. Plot location, description, and disturbances associated with each plot.

PLOT	State	Nat'l Forest	Elev. (m)	Pre-Estbl. Harvest Date	Pre-Estbl. BA removed[1]	Estbl. Date	#Live Trees[2]	Disturbances[3] Estbl.-1950	Disturbances[3] 1950-1999
CIBS1A	NM	Cibola	2610	1910	*	1910	105		tfb
CIBS2A	NM	Cibola	2500	1891	*	1910	125		
COCS1A	AZ	Coconino	2240	1894	10.5	1909	26	sh	tfb
COCS1B	AZ	Coconino	2240	1894	2.9	1909	25		tfb
COCS2A	AZ	Coconino	2250	1895	*	1909	82		
COCS2B	AZ	Coconino	2250	1895	*	1909	72		tfb
COCS3A	AZ	Coconino	2300	1907	10.1	1909	47	sh, pct	pct
COCS3B	AZ	Coconino	2300	1909	9.0	1909	58	sh, pct	pct
COCS4A	AZ	Coconino	2060	1909	8.1	1910	87		sh
COCS4B	AZ	Coconino	2050	1909	5.5	1909	61		sh
COCS5A2	AZ	Coconino	2290	1913	8.7	1913	20	gz	
COCS5B3	AZ	Coconino	2250	1913	5.2	1913	83	gz	
GILAS1A	NM	Gila	2760	1907	7.4	1912	59	dvp	
JEMS2A	NM	Santa Fe	2150	1909	6.2	1911	89		
JEMS3A	NM	Santa Fe	2620	*	12.4	1911	222	sh	sf

[1] BA (m^2) removed = average presettlement tree (>=37.0 cm DBH) stump diameter (1997-1999 field measurement; calculated as BA x number of stumps on historical maps; * = unknown

[2] Number of residual live trees (TPH) in 1909-1913

[3] Disturbance key: sh = selective overstory harvest; tfb = thinning from below; pct = precommercial thinning from below; sf = surface fire; gz = livestock grazing; dvp = development (road construction, utility lines, etc.)

Table 1.3. Definitions used to classify ponderosa pine trees into broad age classes for Objectives 2-6.

Term	Definition	Reference
Blackjack	Ponderosa pine less than 150 years of age. Bark is dark brown-black with narrow furrows.	Woolsey 1911 (refined by Thomson 1940)
Yellow pine	Ponderosa pine tree greater than or equal to 150 years of age. Bark is orange in color with wide furrows.	Woolsey 1911 (refined by Thomson 1940)
Presettlement	Established prior to disruption of the natural frequent fire regime and widespread Anglo-American and Hispanic settlement of the area. Usually greater than or equal to 37 cm (14.6 in) DBH and yellowing bark.	White 1985
Postsettlement	Established after fire regime disruption and Anglo-American and Hispanic settlement of the area. Usually less than 37 cm (14.6 in) DBH.	White 1985
Sapling	Tree regeneration greater than 30.5 cm (12 in) in height and less than 9.14 cm (3.6 in) DBH.	This study. Called "seedlings" and "reproduction" by Woolsey 1911.
Seedling	Tree regeneration less than 30.5 cm (12 in) in height	This study. Individual seedlings not tallied on larger plots in 1909-1913; noted on stem maps.

<u>Objective 3:</u> Reconstruction of forest structure at plot establishment on 15 plots in AZ and NM; *and*

<u>Objective 4:</u> Reconstruction of presettlement structure on 15 plots in AZ and NM

By: A. J. Sánchez Meador and D. W. Huffman

Background and Methods: Tree structural remains are important in forest reconstruction to determine fire history and structural characteristics of past stand conditions (Fulé et al. 1997, Mast et al. 1999); or to determine the effects of partial cutting on tree composition and stand growth (Deal and Tappeiner 2002). The precision of these analyses is highly dependent on field identification of presettlement evidence, dendrochronological proficiency, and relationships utilized in "reverse" growth and decay modeling. While a potential source of error in stand reconstruction approaches is the failure to recognize the evidence of former tree structures or locations in the field (e.g., snags, stumps, down logs, stump hole, etc.), additional error can be linked to the imprecise reconstruction tree diameters to their former size. These types of errors could lead to over- or underestimates in tree sizes and incorrect estimates of pre- or postsettlement forest stand densities (Fulé et al. 1997, Mast et al. 1999, Moore et al. 2004). Our objective in this portion of the study was to use contemporary data from historically measured forest plots in Arizona and New Mexico from 1909-1913, combined with historical data and accounts of past harvesting activities, to reconstruct stand conditions at plot establishment (1909 – 1913) and fire exclusion dates (1876 – 1890), and then to test the precision of our forest reconstruction techniques. Specifically, we wanted to compare our reconstructed stand conditions at plot establishment to those recorded in the historical data in an effort to identify and quantify estimate error.

We reconstructed forest structural conditions at the date of plot establishment (Objective 3), and at the approximate date of fire exclusion (Objective 4). Reconstruction techniques used in southwestern ponderosa pine forests include field identification of tree structural evidence (snags, logs, stumps, etc.), dendrochronological measurement of increment cores from stumps, logs, and living trees, direct measurement of remnant woody evidence, backwards radial growth modeling (Fulé et al. 1997), and decomposition modeling (Rogers et al. 1984).

Previously, Moore et al. (2000, 2004) found that relocating mapped and recorded trees from subplots established between 1909 through 1913 had an associated error rate of 5.7% for Arizona and 11.5% for New Mexico subplots. The majority of the missed trees were small (< 30.0 cm DBH in 1909 – 1913) for all subplots (AZ: 78%, NM: 85%). Additionally, many of the missed trees had died before our remeasurements (AZ: 66%, NM: 47%). It was also found that many of the missed trees existed as highly decomposed structures (i.e., stump holes).

Diameter reconstruction of historical trees that were still alive on Arizona and New Mexico subplots at remeasurement overestimated DBH by an average of 11.9 % and 1.7%, respectively. Moore et al. (2000) also reported large errors (> 60 %) for diameter reconstruction of trees for which increment data were unavailable (rotten tree centers, incomplete cores, etc) and considered this result "unexpected." Further investigation leads one to believe this phenomenon may be a result of the regression equation (ERI Grand Canyon National Park experimental block data collected in January 1998, n = 315, $r^2 = 0.45$; Fulé et al. 2002) used to grow these trees backward in time. In addition, the equations developed by Fulé et al. (2002) were developed to model growth of mature trees (based on data from trees ≥ 100 yrs up to several hundred yrs) for presettlement tree reconstruction; and it is likely that these older trees grow more slowly than the younger trees that potentially dominated the Woolsey plots.

Diameter reconstruction of trees that died (natural mortality or harvesting) after plot establishment (1909-1913) can be problematic. Often the error associated with reconstructing dead structures is unknown; however the use of long-term plots can make us aware of the magnitude and trend of these errors. Error for diameter reconstruction of trees that were alive at plot establishment but were snags and dead and downed at remeasurement was previously computed for the Arizona and New Mexico subplots (Moore 2000). For Arizona subplots, the reconstructed size of these trees was overestimated by 1.5% when moved through decay classes at the 50th percentile rate. Using the same methods, New Mexico trees were underestimated by 7.9% for the 25th decay percentile.

One of the largest difficulties encountered when reconstructing past stand conditions is estimating death date of trees harvested **after** plot establishment (1909 – 1913) that have undergone years of decomposition. When these plots were initially established, the original intent was to harvest each subplot only once prior to or simultaneous with plot establishment (Woolsey 1911). Unfortunately, this was not the case and some plots received multiple harvests after establishment (Moore et al. 2004). We utilized historical records and additional ledger data to determine the most accurate death date for each tree and then incorporated these into the modeled reconstructions for each Arizona and New Mexico subplots (Table 3.1). We assigned trees to their correct death dates on the basis of 1) lists of tree numbers cut (intermediate harvests), and 2) physical characteristics of stumps (diameter, stump height, cutting method, etc).

Results and Discussions: Reconstruction of Plot Establishment Structures: The resulting density, size characteristics, and error associated with assignment of cut dates are summarized in Table 3.2 for the reconstructions incorporating more accurate cut dates (Modeled). Reconstructed subplot densities were higher than those recorded on historical maps. Total number of reconstructed trees on subplots represents the sum of: (1) historically measured trees, (2) trees historically existing on subplots yet too small (< 9.14 cm) to be mapped at original plot establishment, (3) trees that had died or had been cut prior to plot establishment, and (4) large live trees for which no increment core existed. Thus, if a tree's DBH was overestimated when reconstructed to 1909-1913 then that tree was included in the plot totals for tree size and density, when in reality it would have been too small in 1909-1913 to have been measured.

The reconstructions of the Arizona plots resulted in plot density overestimates of 21-162 trees per subplot (Table 3.2: Modeled) even with the more accurate harvest date information. Since the harvested trees' death dates were determined, the resulting overestimation must have come from snags and dead and downed trees for which death dates were inaccurately estimated, and from the backwards radial growth modeling of reconstructed dead material and large live trees for which no increment data was available. Furthermore, the regression equation used increases the error associated with the decomposition estimates and confounds determining if the true source of the overestimation is tree size. We are confident that assigning the correct tree death dates increased the accuracy of the number of trees reconstructed at plot establishment, but it must be noted that this resulted in larger errors associated with those trees' sizes than found by Moore et al. (2000).

Reconstructed tree densities on New Mexico subplots had no clear trend when related to those recorded on historical maps (Table 3.2: Modeled). Totals resulted in error rates that ranged from an underestimate of five trees (JEMS2A) to an overestimate of 222 trees (GILAS1A) per plot.

Overestimation of tree size, together with death date and cut date uncertainties, may lead to overestimates of past tree density. Our reconstruction techniques minimized cut date uncertainties based on historical ledger accounts, but still overestimated tree size and, therefore density. Possible refinements of the reconstructions process might include further error analysis associated with the decay functions and the backwards radial growth regression utilized. Further investigation in these areas of the model may allow better accuracy in stand density reconstruction.

Results and Discussions: Reconstruction of Presettlement Structures: Information gained from analysis of size reconstruction of decomposed snags and dead and downed trees previously found by Moore et al. (2000) were used to parameterize the reconstruction live tree diameters at fire exclusion dates (AZ: 1876, NM: 1890). For plots, the model was set to move trees through decay classes at the appropriate percentile (AZ: 0.50, NM: 0.25), to cut post-plot establishment trees as outlined (Table 3.1), and to cut trees harvested before plot establishment in the year they were harvested (1891-1913). The resulting DBH estimates were not adjusted as previously done. Resulting Arizona plot presettlement densities ranged from 32 to 157 trees per plot (≈ TPH) in Arizona to 117 to 277 for New Mexico (Table 4.1). Slightly lower presettlement densities have been reported, ranging from 56-60 TPH near Woolsey plots in northern Arizona (Covington and Moore 1994, Mast et al. 1999). Increases in density from fire exclusion to the present ranged up to 29-fold, although plots COCS4A and COCS4B showed only slight increases (Figure 4.1; Table 4.1).

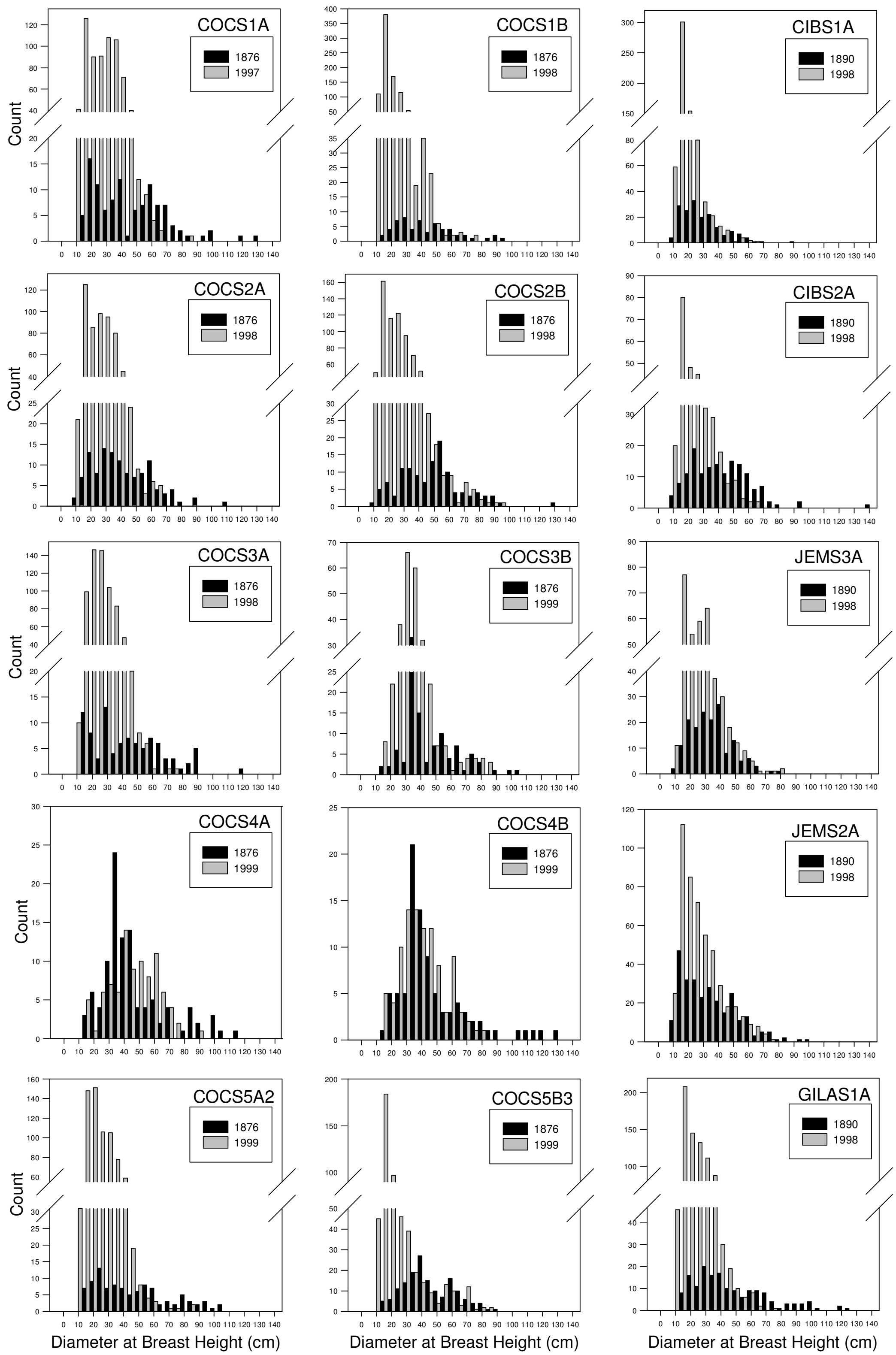
Diameter distributions (all live trees > 1.4 m in height; ≥ 9.14 cm DBH) reveal that the largest increases have occurred in the smallest size classes over this approximate 120-year period. Figure 4.1 shows a comparison of diameters for trees reconstructed at fire exclusion and contemporary (1997-1999) dates. Tree recruitment since fire exclusion has shifted diameter distributions to negative exponential forms.

Summary:

Tree structural remains are important in forest reconstruction to determine fire history and structural characteristics of past stand conditions (Fulé et al. 1997, Mast et al. 1999); or to determine the effects of partial cutting on tree composition and stand growth (Deal and Tappeiner 2002). The precision of these analyses is highly dependent on field identification of presettlement evidence, dendrochronological proficiency, and relationships utilized in "reverse" growth and decay modeling. While a potential source of error in stand reconstruction approaches is the failure to recognize the evidence of former tree structures or locations in the field (e.g., snags, stumps, down logs, stump hole, etc.), additional error can be linked to the imprecise reconstruction tree diameters to their former size.

Overestimation of tree size, together with death date and cut date uncertainties, may lead to overestimates of past tree density. Our reconstruction techniques minimized cut date uncertainties based on historical ledger accounts, but still overestimated tree size and tree density on the plots Possible refinements of the reconstructions process might include further error analysis associated with the decay functions and the backwards radial growth regression utilized.

List of Figures for Objective 3 and Objective 4.


COCS1A
1876
1997
COCS1B
1876
1998
CIBS1A
1890
1998
COCS2A
1876
1998
COCS2B
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CIBS2A
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1999
COCS4B
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1999
JEMS2A
1890
1998
COCS5A2
1876
1999
COCS5B3
1876
1999
GILAS1A
1890
1998
Count
Diameter at Breast Height (cm)

Table 3.1. Cut dates used in reconstructions of trees (≥ 9.14 cm DBH) harvested on Arizona and New Mexico subplots: initial – initial harvest date, intermediate – some harvest activity took place on plot at dates indicated, final – last harvest on plot.

		Establishment	Harvest Dates		
	Subplot	Date	Initial	Intermediate	Final
Arizona	COCS1A	1909	1894	1941	1980
	COCS1B	1909	1894	1941	1980
	COCS2A	1909	1895	1941	1980
	COCS2B	1909	1895	1941	1980
	COCS3A	1909	1907	1941	1980
	COCS3B	1909	1909	1941	1980
	COCS4A	1909	1909	1967	-
	COCS4B	1909	1909	1967	-
	COCS5A2	1913	1913	-	1980
	COCS5B3	1913	1913	-	1980
New Mexico	CIBS1A	1910	1910	-	1980
	CIBS2A	1910	1891	-	1980
	GILAS1A	1912	1907	1932	1980
	JEMS2A	1911	1909	-	-
	JEMS3A	1911	1910*	-	-

*Harvest date unknown; so assumed initial harvest occurred year prior to plot establishment

Table 3.2. Comparison of reconstructions of trees (≥ 9.14 cm DBH) harvested prior to or simultaneously with plot establishment (1909-1913) for Arizona and New Mexico plots compiled from historical ledgers (Actual) and modeled by assigning accurate harvest dates to trees on each plot (Modeled). StdDev (%; last column) is standard deviation of the Error.

Arizona		Actual			Modeled				
	Subplot	Live Trees	Mean DBH (cm)	Std.Dev. (cm)	Live Trees	Mean DBH (cm)	Std.Dev. (cm)	Error % (n)	StdDev (%)
	COCS1A	26	36.3	13.1	176	21.7	15.0	31.5 (5)	23.1
	COCS1B	25	50.8	20.0	61	36.5	24.3	-5.7 (14)	53.0
	COCS2A	82	41.7	21.3	244	24.4	18.4	-11.4 (15)	29.3
	COCS2B	72	39.9	20.4	213	27.7	20.6	29.9 (14)	30.4
	COCS3A	47	33.9	17.2	73	39.0	19.9	47.8 (18)	51.3
	COCS3B	58	41.1	15.1	79	43.4	14.6	21.2 (21)	31.1
	COCS4A	87	30.9	14.7	110	42.4	20.3	55.2 (36)	56.1
	COCS4B	61	35.1	15.6	93	47.2	24.9	44.2 (33)	34.5
	COCS5A2	20	37.1	24.9	133	38.9	25.0	7.8 (4)	23.4
	COCS5B3	83	37.2	15.4	160	43.1	17.4	21.7 (7)	18.6
	Mean	56.1	38.4	17.8	134.2	36.4	20.0	24.3	35.1

New Mexico		Actual			Modeled				
	Subplot	Live Trees	Mean DBH (cm)	Std.Dev. (cm)	Live Trees	Mean DBH (cm)	Std.Dev. (cm)	Error % (n)	StdDev (%)
	CIBS1A	105	28.0	14.4	207	26.2	14.2	44.9 (6)	46.4
	CIBS2A	125	32.8	14.2	129	31.0	15.6	21.3 (53)	37.9
	GILAS1A	59	27.0	12.2	281	28.5	20.0	16.6 (1)	-
	JEMS2A	89	26.1	8.9	-	-	-	-	-
	JEMS3A	222	29.4	9.4	-	-	-	-	-
	Mean	120	28.6	11.8	205.7	28.6	16.6	27.7	42.2

Table 4.1. Reconstructed tree structural characteristics (≥ 9.14 cm DBH) on historical plots at the time of fire exclusion (AZ: 1876, NM: 1890) and the number of live trees at the time of remeasurement (1997-1999).

Arizona	Subplot	Live Trees Date: 1876	Mean DBH (cm)	Std.Dev. (cm)	Live Trees Date: 1997-1999
	COCS1A	110	44.1	25.7	710
	COCS1B	32	35.1	14.4	928
	COCS2A	118	38.6	19.5	596
	COCS2B	78	52.0	20.8	753
	COCS3A	37	47.6	23.4	670
	COCS3B	105	42.5	18.0	282
	COCS4A	106	42.6	21.3	91
	COCS4B	90	44.2	23.5	99
	COCS5A2	101	43.8	24.3	571
	COCS5B3	157	42.3	16.6	499
	Mean	93.4	43.3	20.8	519.9
	Std.Dev.	37.2	4.5	3.6	280.1

New Mexico	Subplot	Live Trees Date: 1890	Mean DBH (cm)	Std. Dev. (cm)	Live Trees Date: 1997-1999
	CIBS1A	117	27.6	13.8	649
	CIBS2A	151	39.4	19.2	278
	GILAS1A	162	44.0	24.7	807
	JEMS2A	162	32.1	13.6	356
	JEMS3A	277	31.6	17.9	497
	Mean	173.8	34.9	17.9	517.4
	Std.Dev.	60.6	6.6	4.6	215.0

Objective 5: Ecosystem changes from 1876 to 2002: A case study of COCS1A

By: D. W. Huffman, J. D. Bakker, D. M. Bell, and M. M. Moore

Background and Methods:

Readers' note: In objectives 2-4 the analyses were restricted to a smaller subplot (1.01 ha) of this larger one. Objectives 5 and 6 analyze the entire plot area of COCS1A (2.59 ha) and the results therefore differ slightly from those reported in earlier objectives.

Temporal and spatial modeling requires a tremendous amount of data and computing power. If a mistake is made, it is difficult to find the error if many plots are analyzed simultaneously. Therefore, we chose to examine a single plot for objectives 5 (ecosystem changes) and 6 (spatial pattern changes) so that we might work through all of the techniques and procedures and set up analytical routines on this prototype plot. Temporal and spatial analyses will be extended to additional plots soon.

The plot we chose for this case study was COCS1A (see Fig. 1.2 in General Methods). COCS1A is located on the Fort Valley Experimental Forest approximately 10 km NW of Flagstaff. The overstory vegetation is ponderosa pine and the understory vegetation is predominantly perennial bunchgrasses. The elevation is 2240 m. The soils are Mollic Eutroboralfs and Typic Argiborolls, primarily with clay loam and stony clay textures. This plot is 6.4 ac or 2.59 ha (160 x 160 m) in size.

COCS1A was established in 1909 (the first plot established by Gus Pearson). It was harvested prior to plot establishment in 1894 by Greenlaw Lumber Company. In 1909 the entire plot had 134 residual trees (52 TPH). This plot was also thinned from below in 1941.

Objective 5: We examined how documented changes in overstory structure have affected ecosystem function such as overstory biomass accumulation, nutrient storage, understory biomass production, and fire behavior. Forest structural and ecosystem changes were examined for the following points in time: 1) 1876 (fire exclusion date) using tree numbers and sizes obtained via the reconstruction techniques explained in Objective 4; 2) 1909-1949 in 5-year increments using tree numbers and sizes obtained from historical ledgers; and 3) 2002 (our remeasurement; based on 2001-2002 data). All analyses were conducted on trees ≥ 9.14 cm DBH. All production estimates have been converted to SI units for presentation and discussion. Ledger data are stored in the Fort Valley Archives, USFS RMRS, Flagstaff, AZ.

Additional methods and analyses for changes in overstory structure, overstory biomass, overstory nutrients, understory production, and fire behavior are described in the following paragraphs.

Overstory Structure: Data collection for basic overstory structure was described in the 'General Methods' section. Basic overstory variables calculated at each date listed above include stand density (TPH), basal area, quadratic mean diameter, and Reineke's Stand Density Index (Avery and Burkhart 2002).

The crown area of each tree was calculated using an allometric equation relating crown radius to tree diameter (Table 5.2). The crown area of each tree was summed to yield a total crown area, and the total crown area was divided by the total plot area (25,900 m^2) to yield the proportion of the plot occupied by crowns. This method of calculating canopy cover yields a high estimate, as it does not account for crown overlap.

The diameter and age (center date at 40 cm height) distributions of the plot at present were examined using all trees > 1.4 m tall (in comparison, all other analyses here focus on trees ≥ 9.14 cm DBH).

Overstory Biomass: We used allometric equations relating foliage, branch, bark, stemwood, and coarse root weight to tree diameter (Table 5.1) to estimate component biomass of trees.

Changes in leaf area index (LAI; m^2/m^2) over time were estimated using equations that relate fascicle weight to tree diameter, and fascicle surface area to fascicle weight (Table 5.1). Number of fascicles per tree was estimated by dividing foliage weight per tree by weight per fascicle. We calculated projected leaf surface area per tree by taking the product of the number of fascicles per tree and one-sided fascicle area surface area (Cable 1958). LAI was estimated by summing fascicle surface area of all trees and dividing by the total plot area (25,900 m^2).

Overstory Nutrients: We estimated nutrients (kg/ha) stored in trees using values for average nitrogen (N), phosphorus (P), and potassium (K) content of biomass components for ponderosa pine trees in southwestern Idaho (Clayton and Kennedy 1980). We found no other published studies providing a comprehensive analysis of component nutrient content. However, values given by these authors for nitrogen content were similar to those reported for ponderosa pine tree components in northern Arizona (Klemmedson 1975) and foliage in the Great Basin (Poth and Fenn 1998). Nutrient percentages used are given in Table 5.2.

Understory Biomass: Understory production (kg/ha) was estimated using allometric equations developed at Gus Pearson Natural Area (< 1 km from COCS1A), the Wild Bill Range, and the Beaver Creek Watershed (Table 5.3). We used three equations to see if they are predicting similar trends in production over time.

Forest floor depth (cm) was predicted using equations developed in fire-excluded forests at the Beaver Creek watershed and other sites throughout northern Arizona (Table 5.3).

Fire behavior: The Forest Vegetation Simulator (FVS) and the Fire and Fuels Extension (FFE-FVS) were used to examine temporal changes in forest structure and historical and contemporary fire behavior from 1876 to 2002. The Southwestern Ponderosa Pine Model of the Central Rockies GENGYM Variant was designated as the most appropriate for ponderosa pine stands in Northern Arizona (Dixon 2001). 'Suppose' Vers.1.16, a graphical interface for FVS, was used to import data and run stand simulations. Changes in stand structure were considered based on stand density (TPH) and basal area (m^2/ha) as determined above in "Overstory Structure". FFE-FVS was used to quantitatively analyze fire behavior using crowning index (km/h) as an indicator of potential for extreme fire behavior. Crowning index depends on canopy bulk density (driven by tree growth and density), slope steepness (a static environmental condition), and surface fuel moisture (a product of local weather conditions) (Beukema et al. 2003).

Forest inventory data required formatting before it could be inputted into FVS. Inventory data was modified using Format4FVS V1.1. Minimum FVS data for individual trees included tree number, DBH, tree species, and tree status (dead or alive); tree height and crown ratio were also used when available.

Historic weather data were located for the Flagstaff Remote Automated Weather Station (RAWS) for 1968-2003 (USDA 2004). All analyses were based on June weather since June is historically the driest and most fire-prone month for much of northern Arizona. Estimates of 50^{th} and 97^{th} percentile fire weather conditions based on RAWS data included diurnal high temperature, 20 foot wind speed, and fuel moistures for 1, 10, 100, and 1000 hour fuels; estimates were made using Fire Family Plus V3.04. These weather conditions were taken as proxies for moderate and severe fire weather conditions, respectively.

Results:

Overstory Structure: Our reconstruction predicted that the stand density (trees ≥ 9.14 cm DBH) at fire exclusion (1876) was 110 TPH. Harvesting in 1894 reduced the density by more than half; density at plot establishment (1909) was 51 TPH. Between plot establishment and today, stand density increased more than 11-fold to 574 TPH in 2002 (Fig. 5.1a). However, 86% of this increase had already occurred by 1949, when the density was 494 TPH.

Basal area at fire exclusion was about 21 m^2/ha. Harvesting in 1894 removed about two-thirds of this area so that the basal area at plot establishment was only 5.8 m^2/ha. Since then, basal area has increased 6-fold to 38.6 m^2/ha today (Fig. 5.1b). Basal area has continued to accumulate and is not leveling off as tree density did. Basal area in 1949 was equal to that at fire exclusion and only 54% of that in 2002.

Quadratic mean diameter (QMD) was highest (49.4 cm) at fire exclusion and then declined to a low of 22.4 cm in 1924 before slowly rising again (Fig. 5.2a and Fig. 5.3). By 2002, QMD was 29.3 cm. Reineke's Stand Density Index was 319 at fire exclusion and 98 at plot establishment, and has since risen to 720 in 2002 (Fig. 5.2b). Canopy cover declined from 30% at fire exclusion to 9% in 1909 and then rose to 59% today (Fig. 5.2c).

Figure 5.3 also illustrates changes in diameter distributions for COCS1A from fire exclusion to 2002 using 5 cm diameter classes. This figure includes a comparison of 1909 actual data and reconstructed data (as if the 1894 harvest had never happened on this plot). TPH, basal area, QMD, and diameter distribution trends are similar to those seen in figures 5.1, 5.2, and 5.4.

The 2000 diameter distribution was dominated by small trees (Fig. 5.4a); in addition to the 574 TPH ≥ 9.14 cm DBH there are another 177 TPH which are < 9.14 cm DBH. The 2000 age distribution is dominated by a regeneration pulse from the early 1900s; 42% of trees reached a height of 40 cm between 1900 and 1919 (Fig. 5.4b).

NOTE: The "dip" in the overstory structure variables and other variables that follow (biomass, nutrients, etc.) in 1944 is due to two major factors: 1) harvesting of some trees on this plot in 1941, and 2) not recording ingrowth in 1944 (all ingrowth after 1939 was recorded in 1949).

Overstory Biomass: Total tree (≥ 9.14 cm DBH) biomass decreased from 169,924 kg/ha in 1876 to 33,431 kg/ha in 1909 (Fig. 5.5a). After 1909, total tree biomass showed a roughly linear increase until 2002 when it reached 202,465 kg/ha. Thus, from date of fire exclusion and plot establishment to contemporary conditions, total tree biomass increased by 19 and 600%, respectively. The proportion of biomass allocated aboveground has increased from 78% in 1876 to 81% in 1909 and 82% in 2002.

Leaf area index decreased from 1.9 m^2/m^2 in 1876 to 0.6 m^2/m^2 in 1909 (Fig. 5.5b). From plot establishment to 2002, LAI increased to 3.8 m^2/m^2.

Overstory Nutrients: N stored aboveground in trees decreased from 608 kg/ha in 1876 to 129 kg/ha in 1909 (Fig. 5.6a). Foliage accounted for 12.5% (76 kg/ha) of the N in 1876 and 16% (21 kg/ha) of the N in 1909. Aboveground P decreased from 15 kg/ha at fire exclusion to 4 kg/ha at plot establishment (Fig. 5.6b). Potassium also decreased, from 125 kg/ha in 1876 to 28 kg/ha in 1909 (Fig. 5.6c).

Since 1909, N has increased to 799 kg/ha in 2002, which represented an increase of more than 600% since plot establishment. N levels in 2002 are 31% higher than those in 1876 (Fig. 5.6a). The foliage accounted for 17% (138 kg/ha) of the N in 2002. Foliar N has increased 550% since plot establishment and 82% since fire exclusion. P and K showed similar changes; aboveground storage in trees was 23 kg/ha and 176 kg/ha in 2002 for the two nutrients, respectively. For P, this represented increases of 475% and 53% since plot establishment and fire exclusion dates, respectively. For K, increases were 528% and 41% since plot establishment and fire exclusion, respectively (Fig. 5.6b and 5.6c).

Understory Biomass: The equation developed at the Wild Bill Range has a different form than the other two at low basal areas (Fig. 5.7a). The equation developed on the Beaver Creek watershed was based on average annual production values for each plot and is less affected by interannual climatic variation than the other two equations (Bojorquez-Tapia et al. 1990). The prediction from this equation is very similar to the average of the three equations, on which we based our analyses (Table 5.3).

Understory production more than doubled between 1876 and 1909, and this variable is predicted to be only 64 kg/ha (6.4 g/m^2) at present. This represents a reduction of 54% compared to the predicted production in 1876 and a reduction of 83% compared to the predicted production in 1909.

The forest floor is predicted to have been about 2.5 cm in 1876 and to have declined to 1.5 cm in 1909 (Fig. 5.7b). Since plot establishment, the predicted forest floor depth has increased to 2.5 cm in 1949 and to 3.4 cm at present.

Fire Behavior: 50th and 97th percentiles for June 1968-2003 fuel moisture, wind speed, and temperature for the Flagstaff Weather Station are found in Table 5.4. Crowning indices for moderate (50th percentile) and severe (97th percentile) fire weather are shown in Fig. 5.8. Under these conditions, crowning index rose between 1876 and 1909 and then declined rapidly until the 1930's, after which reductions occurred more slowly (Fig. 5.8). Similar trends are evident for both moderate and severe fire weather, though crowning indices were always lower for severe than moderate fire weather.

Discussion:

Overstory Structure: Stand density, basal area, and quadratic mean diameter decreased from fire exclusion (1876) to 1909 (Fig. 5.1, Fig. 5.2) due to the harvest that occurred in 1894. This harvest extracted over 50% of the trees and two-thirds of the basal area on this plot. The reduction in QMD from fire exclusion to 1924 (Fig. 5.2a) also reflects the combined effects of tree harvest and ingrowth of ponderosa pine regeneration. Since then, small trees have died due to self-thinning and the QMD has risen slightly.

Much of the change in stand density had already occurred by 1950 (Fig. 5.1a). Basal area has continued to increase in a linear fashion and is almost twice as large now as at fire exclusion, before any harvesting had occurred (38.6 vs. 21.0 m^2/ha, respectively). Similarly, canopy cover is more than twice as large now as at fire exclusion (Fig. 5.2c).

The age distribution is dominated by trees that reached a height of 40 cm in the early 1900s. Several authors (e.g., Savage et al. 1996) have suggested that the 1919 regeneration pulse produced many of the trees that are present in today's forests. However, assuming that a tree takes at least 3 years to reach 40 cm height, more than half of the trees on COCS1A germinated prior to 1919 (i.e., have a center date < 1922).

Moore et al. (2004) compared the historical (1909) and contemporary (1997) forest structure on a 1 ha subplot of this site. On this subplot, stand density and basal area were lower at plot establishment (26 TPH, 3.0 m^2/ha) than on the entire plot as reported here (51 TPH, 5.8 m^2/ha; Fig. 5.1). Conversely, stand density and basal area in 1997 were higher on the subplot in 1997 (703 TPH, 42.2 m^2/ha) than on the entire plot in 2002 (574 TPH, 38.6 m^2/ha). These differences are due primarily to two factors. First, the northwest corner of the site where the subplot is located is on a basalt outcrop at slightly higher elevation than the rest of the plot. Contemporary tree densities are more than 20% higher on the subplot than on the plot as a whole.

Second, stand densities are declining due to continued tree mortality. On the subplot, 13 trees (1.8%) ≥ 9.14 cm DBH died between 1997 and 2002. Eight trees grew to be ≥ 9.14 cm DBH during this period, so the net result was a reduction of five trees, from 703 TPH to 698 TPH. An additional 27 small trees died and no trees grew to be > 1.4 m tall, so the density of trees < 9.14 cm DBH declined from 239 TPH in 1997 to 204 TPH in 2002.

Overstory Biomass: Tree biomass on COCS1A at fire exclusion date (169,924 kg/ha) reflected the relatively low density (110 TPH) yet high QMD (49.4 cm). Larger trees contributed disproportionately to stand biomass, as reflected in the high wood-foliage biomass ratio (25.9). Tree biomass in aboveground components (131,813 kg/ha; exclusion of coarse root biomass) was approximately 60% greater than that estimated for 1876 by Covington et al. (2002) (81,500 kg/ha) for a site near ours. However, estimated tree density and biomass at fire exclusion was nearly twice as high on COCS1A: 110 vs. 60 TPH and 21 m^2/ha vs. 10.6 m^2/ha, respectively (Mast et al. 1999, Covington et al. 2001). We are aware of no other studies that have estimated presettlement biomass for ponderosa pine forests.

The removal of large trees during the 1894 harvest was reflected by a reduction in wood-foliage biomass ratio (19.2) in 1909. The wood-foliage biomass ratio declined to 15.1 in 1949 and then rose to 17.6 in 2002 as a selective harvest in 1941, together with natural mortality, encouraged diameter growth of individual trees.

Aboveground biomass increased from 1909 (27,097 kg/ha) to 2002 (165,461 kg/ha) with large pulses of tree establishment and stand growth. By 2002, aboveground biomass was within 28% of the value reported by Covington et al. (2001) for 1992 conditions on their site. Contemporary woody plant biomass in a northern Arizona ponderosa pine and Gambel oak (*Quercus gambelii* Nutt.) stand ranged from 405 kg/ha to 81,654 kg/ha as ponderosa pine basal area ranged from 0 m^2/ha (forest opening) to 23 m^2/ha (Clary 1978). Klemmedson (1975) estimated biomass of a dense (22,500 TPH) ponderosa pine stand near COCS1A to be 189,870 kg/ha.

Changes in overstory biomass since fire exclusion represent alteration of forest structure from open stands dominated by large trees, to closed stands of smaller, younger trees. This was clear in our examination of LAI dynamics. Leaf area index doubled from 1.9 at fire exclusion to 3.8 in 2002. Thus, contemporary conditions reflect stands of smaller trees with a high proportion of foliage and leaf area as compared to large trees that have proportionally more stem wood (Cable 1958). The increased proportion of nutrients stored in the foliage in 2002 compared to 1876 (Fig. 5.6) further illustrates this change. Maximum LAI for ponderosa pine stands appears to range from 4.2 to 9.0 m^2/m^2 and to be determined by site productivity (Grier and Running 1977, Gholz 1982, McLeod and Running 1988). The changes we estimated may indicate stand conditions of decreasing tree growth efficiency. For example, Oren et al. (1987) showed that tree growth efficiency (stem volume production per unit of foliage area) decreased exponentially in ponderosa pine trees as LAI increased from 0 to 4 m^2/m^2. Decreased growth efficiency may indicate limitations in tree storage reserves and production of chemical that may provide defense against pests and pathogens (Waring and Schlesinger 1985).

Overstory Nutrients: Our values of 609-799 kg/ha of aboveground N were approximately twice those reported for a dense stand of young ponderosa pine near COCS1A (Klemmedson 1975) but 2-3 times lower than those reported by Covington et al. (2001). This difference may be due to an error in Covington et al. (2001) when they apparently used 11.1% for foliar N, when the value should have 1.0%. Other than this discrepancy due to an error, differences between our estimates and those of other researchers are likely due to real differences in stand conditions as well as differences in values used in calculations.

Changes from 1876 to 2002 in N storage (Fig. 5.6) suggest an increasing proportion of N stored in foliage as compared with N in wood. However, as tree recruitment in COCS1A approaches zero, growth of existing trees and self-thinning of the stand will likely begin to reduce the proportion of aboveground N stored in tree foliage (Covington et al. 2001). In general, changes in overstory nutrient storage suggest diminished nutrient turnover and decreased nutrient availability to other ecosystem components such as understory plants and non-arboreal herbivores (Covington and Moore 1994, Kaye and Hart 1998, Covington et al. 2001).

***Understory Biomass*:** Understory production is reduced at present compared to both fire exclusion and plot establishment. However, the predicted values presented here must be regarded as rough estimates. In particular, the equations predict understory production from basal area but do not account for the distribution of basal area in the stand. This is illustrated by comparing the overstory structure in 1876 and 1949. Basal area was equal at both times (Fig. 5.1b) but density was more than 4 times larger in 1949 (Fig. 5.1a), indicating that there were many small trees. Further analysis of this issue is required but beyond the scope of this report.

The forest floor has increased in depth (Fig. 5.7b), suggesting that it is becoming an increasingly important pool of nutrients. In fact, the forest floor was likely even shallower in presettlement times than reported here, as the allometric equations used to predict it (Table 5.3) were developed in fire-excluded forests. The frequent fire regime during presettlement times would have consumed much of the forest floor, reducing the amount of forest floor present in 1876 below the values calculated here.

Fire Behavior: The dramatic increase in crowning index (reduced likelihood of active crown fire) between 1876 and 1909 (Fig. 5.8) is most likely a result of the 1894 harvest. Crowning indices remained higher than in 1876 until 1924, indicating that the likelihood of active crown fire was also lower. After this time, both extreme and moderate crowning indices begin to approach observable wind speeds for Northern Arizona. The decreasing crowning index since 1909 indicates rapid development of active crown fire conditions and the potential for movement of fire from stand to stand, a driving factor in medium to large fires (Atkins and Lundberg 2002). As slope and weather conditions were held constant during this analysis, increasing tree density (and hence crown bulk density) is the cause for increasing crown fire potential.

It is important to note that the fire weather was derived from daily weather data for the month of June from 1968-2003 and then applied to inventory years from 1876, 1909-1949, and 2002. Reconstructions of the Palmer Drought Severity Index (AD 1700 to 1978) for the Southwestern United States indicate that summer season (June – August) weather was drier during the second half of the 20th century when compared to the first four decades of the century (Swetnam and Baisan 1996). Though June weather may not follow the same trend, overall fire season weather would have been milder during the early-20th century. Even though localized weather conditions may have varied from regional reconstructions, the drier conditions in the late-20th century may have contributed to lower than actual crowning index for the time period under consideration and thus exaggerated fire behavior.

Summary:

Overstory structure on COCS1A has changed significantly between 1876 and 2002. A selective harvest in 1894 significantly reduced the stand density, total basal area, and quadratic mean diameter. Since plot establishment in 1909, density and basal area have increased to levels greatly exceeding those found in 1876. Canopy cover, overstory biomass, leaf area index, overstory nutrients, and forest floor depth are predicted to have increased as basal area increased. Levels of all of these variables in 2002 exceeded the predicted levels in 1876. Understory production is predicted to have declined as basal area increased, and was lower in 2002 than at any other date.

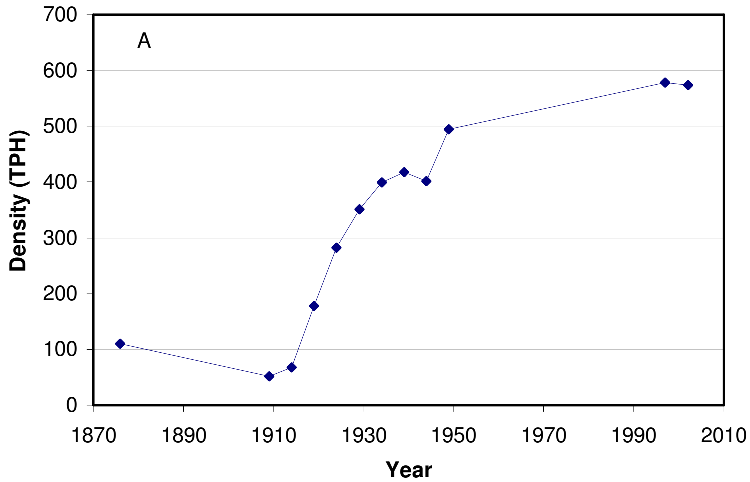
The dip in all variables in 1944 is due to two major factors: 1) harvesting of some trees on this plot in 1941, and 2) not recording ingrowth in 1944 (all ingrowth after 1939 was recorded in 1949).

In 2002, the overstory was dominated by small trees (< 20 cm), many of which first grew to a height of 40 cm between 1900 and 1939.

The crowning indices rose as a result of the 1894 harvest and then decreased over time. The potential to support an active crown fire has increased greatly, and is higher at present than in 1876 or 1909.

The tree harvests of the late 19th and early 20th century, together with fire exclusion, overgrazing, and climate change, altered the trajectory of stand development of ponderosa pine in northern Arizona. These factors must be taken into account in ponderosa pine restoration treatments.

List of Figures for Objective 5.


A
Density (TPH)
700
600
500
400
300
200
100
0
1870
1890
1910
1930
1950
1970
1990
2010
Year

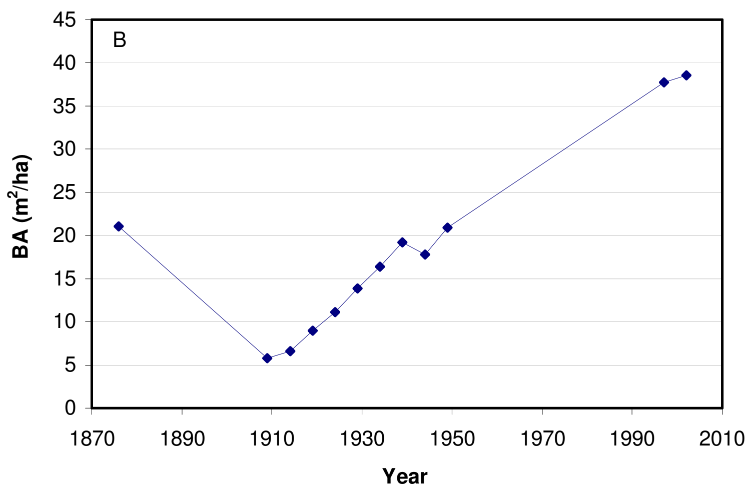

B
BA (m2/ha)
45
40
35
30
25
20
15
10
5
0
1870
1890
1910
1930
1950
1970
1990
2010
Year

Fig. 5.1

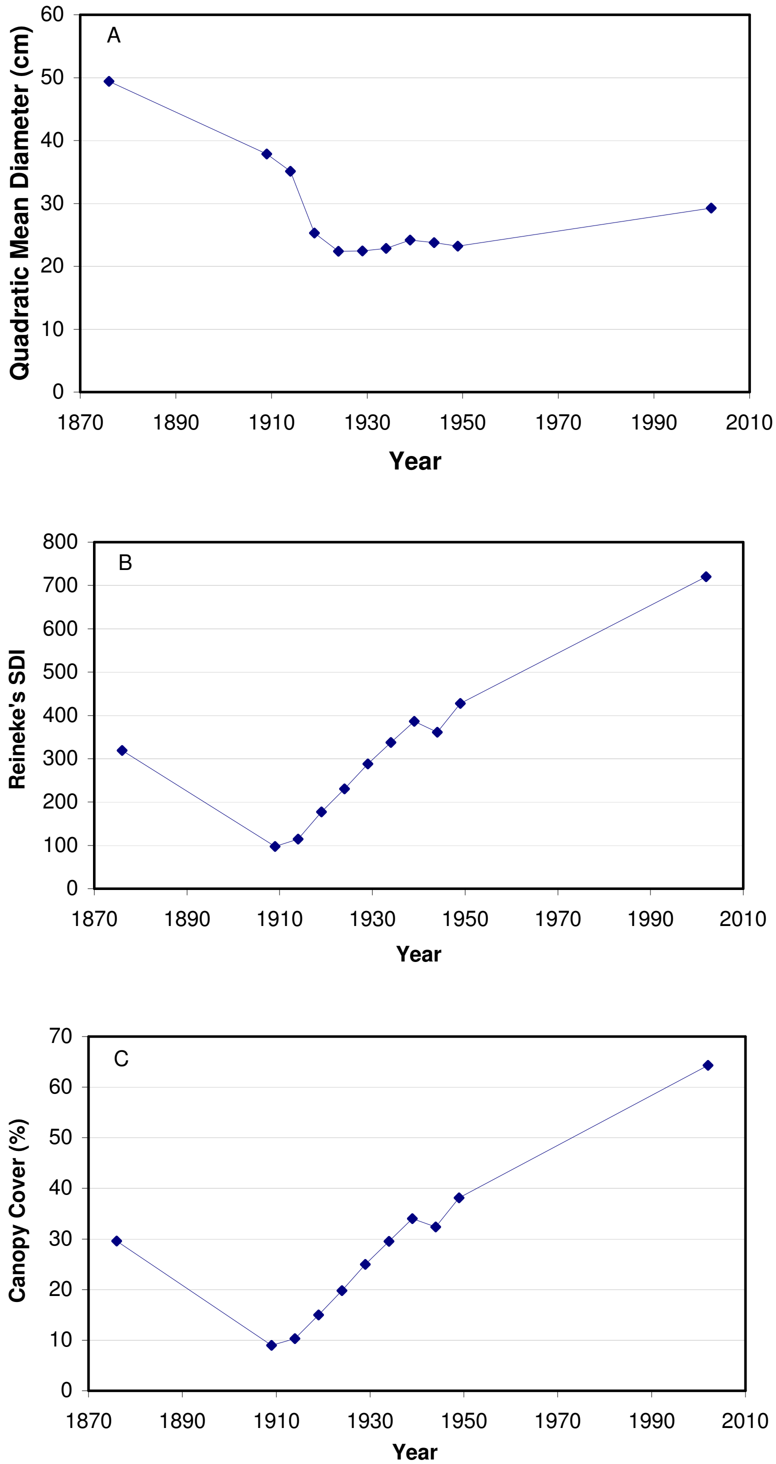
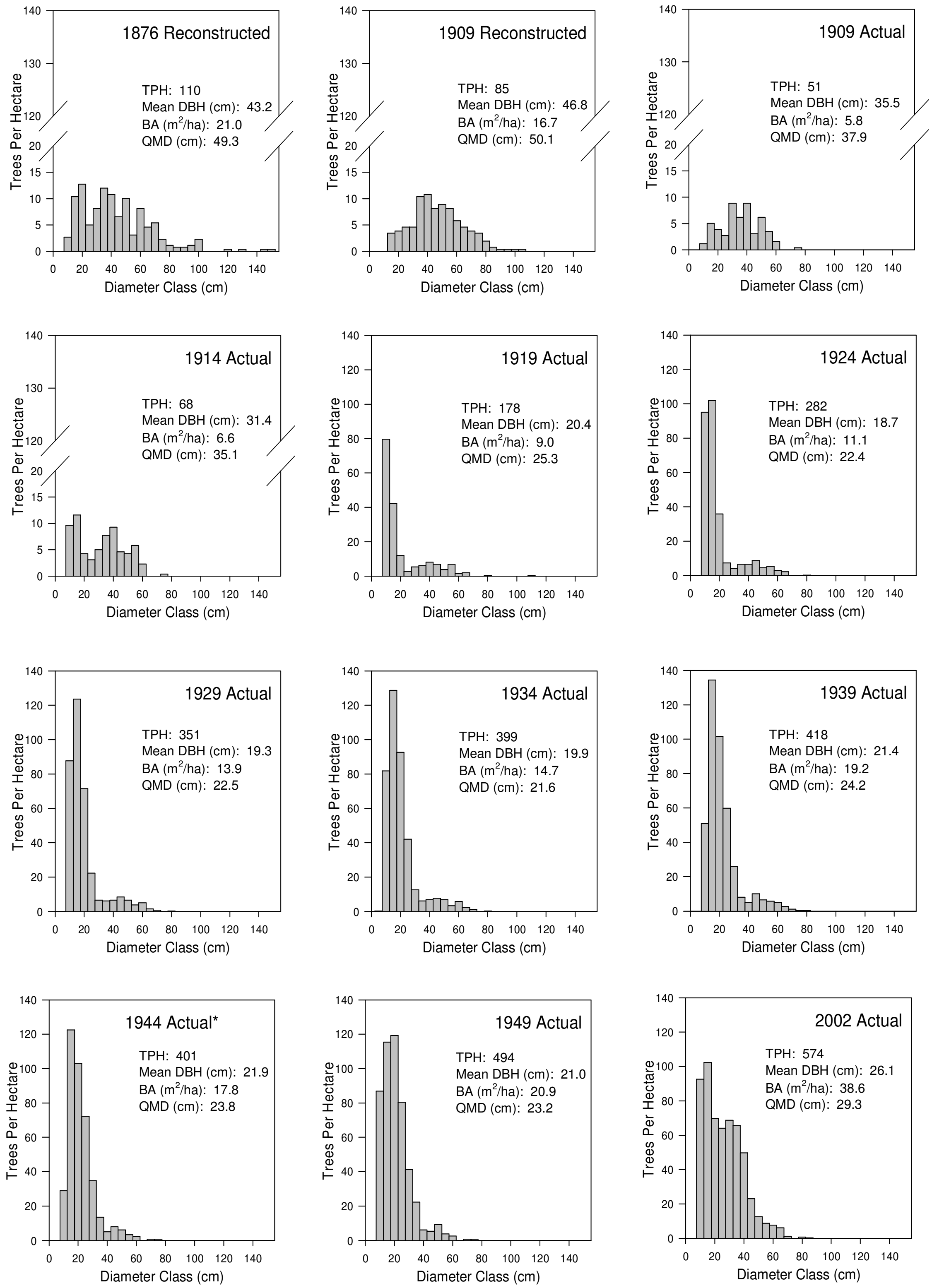

A
Quadratic Mean Diameter (cm)
60
50
40
30
20
10
0
1870
1890
1910
1930
1950
1970
1990
2010
Year
B
Reineke's SDI
800
700
600
500
400
300
200
100
0
1870
1890
1910
1930
1950
1970
1990
2010
Year
C
Canopy Cover (%)
70
60
50
40
30
20
10
0
1870
1890
1910
1930
1950
1970
1990
2010
Year

Fig. 5.2



*Graph depicts diameter distribution in 1944 where no ingrowth was recorded (1944 ingrowth is reflected in figure of 1949)

Fig. 5.3

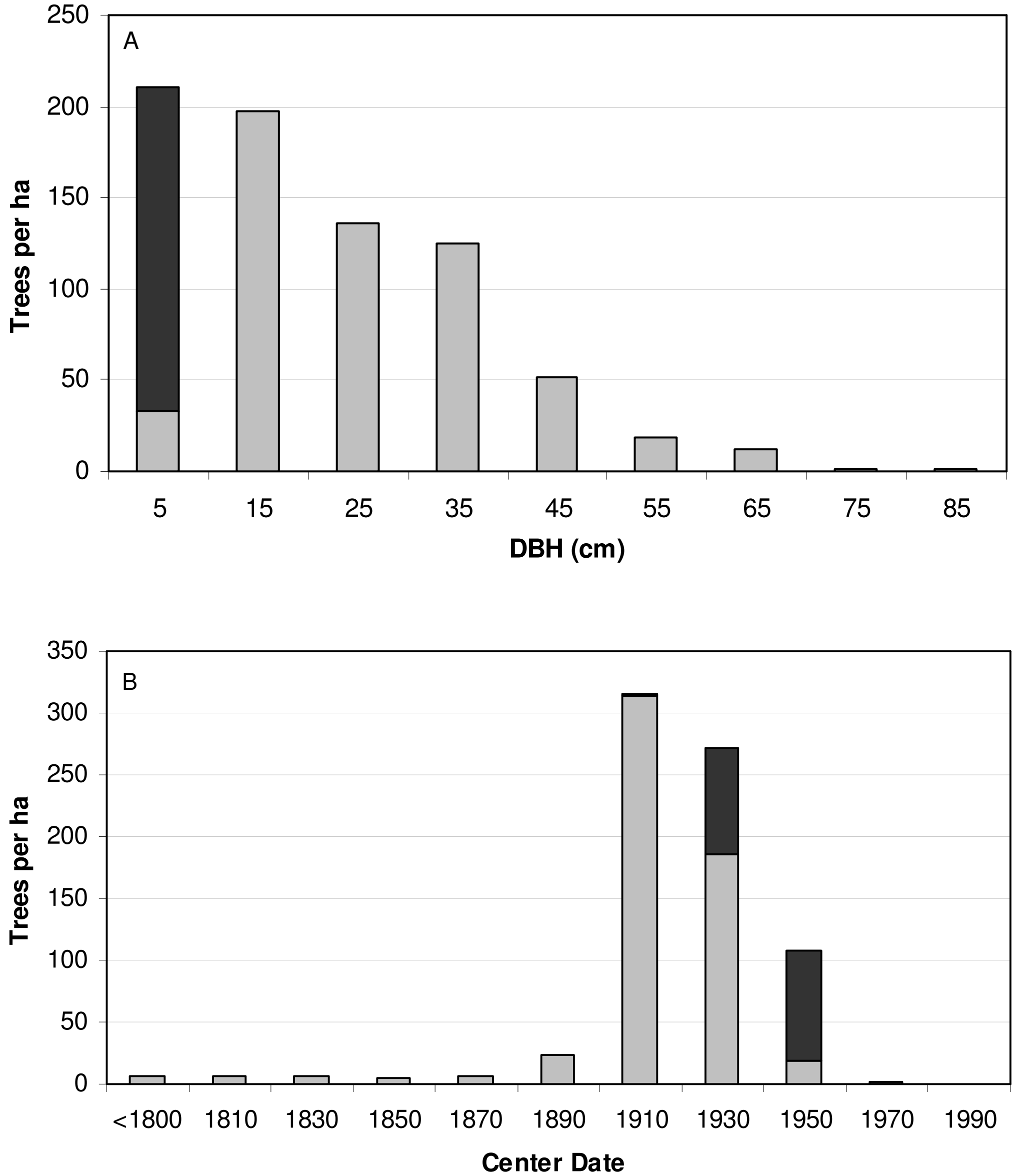
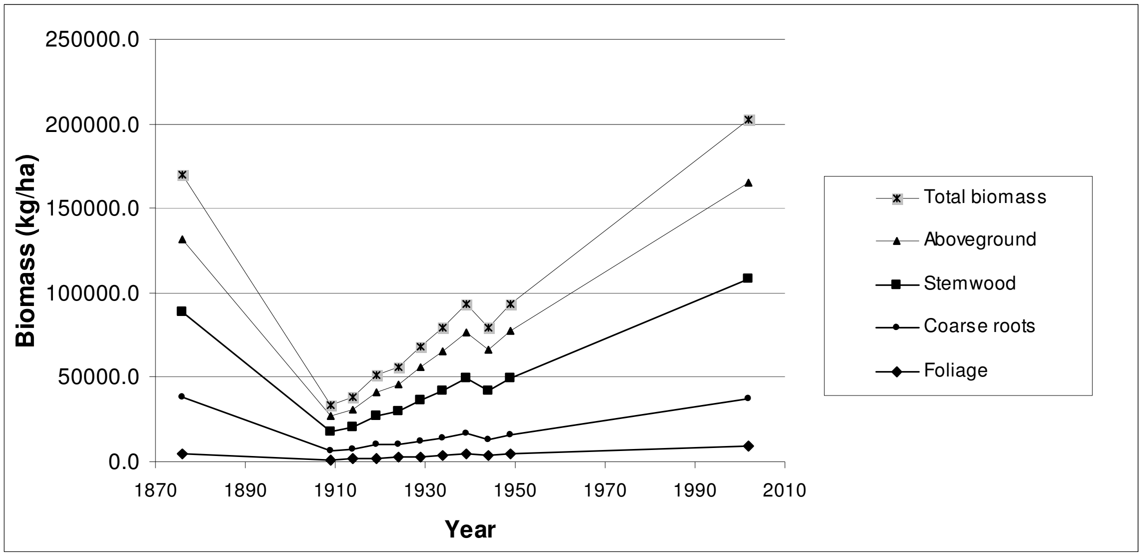

A
Trees per ha
250
200
150
100
50
0
5
15
25
35
45
55
65
75
85
DBH (cm)
B
Trees per ha
350
300
250
200
150
100
50
0
<1800
1810
1830
1850
1870
1890
1910
1930
1950
1970
1990
Center Date

Fig. 5.4


250000.0
200000.0
150000.0
100000.0
50000.0
0.0
Biomass (kg/ha)
1870
1890
1910
1930
1950
1970
1990
2010
Year
Total biomass
Aboveground
Stemwood
Coarse roots
Foliage

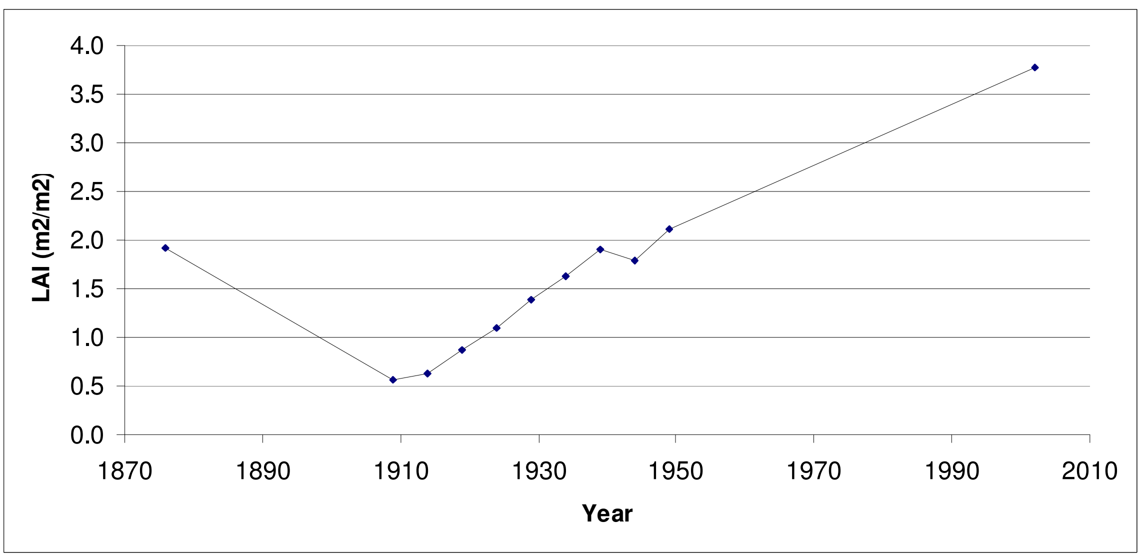

4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
LAI (m2/m2)
1870
1890
1910
1930
1950
1970
1990
2010
Year

Fig. 5.5

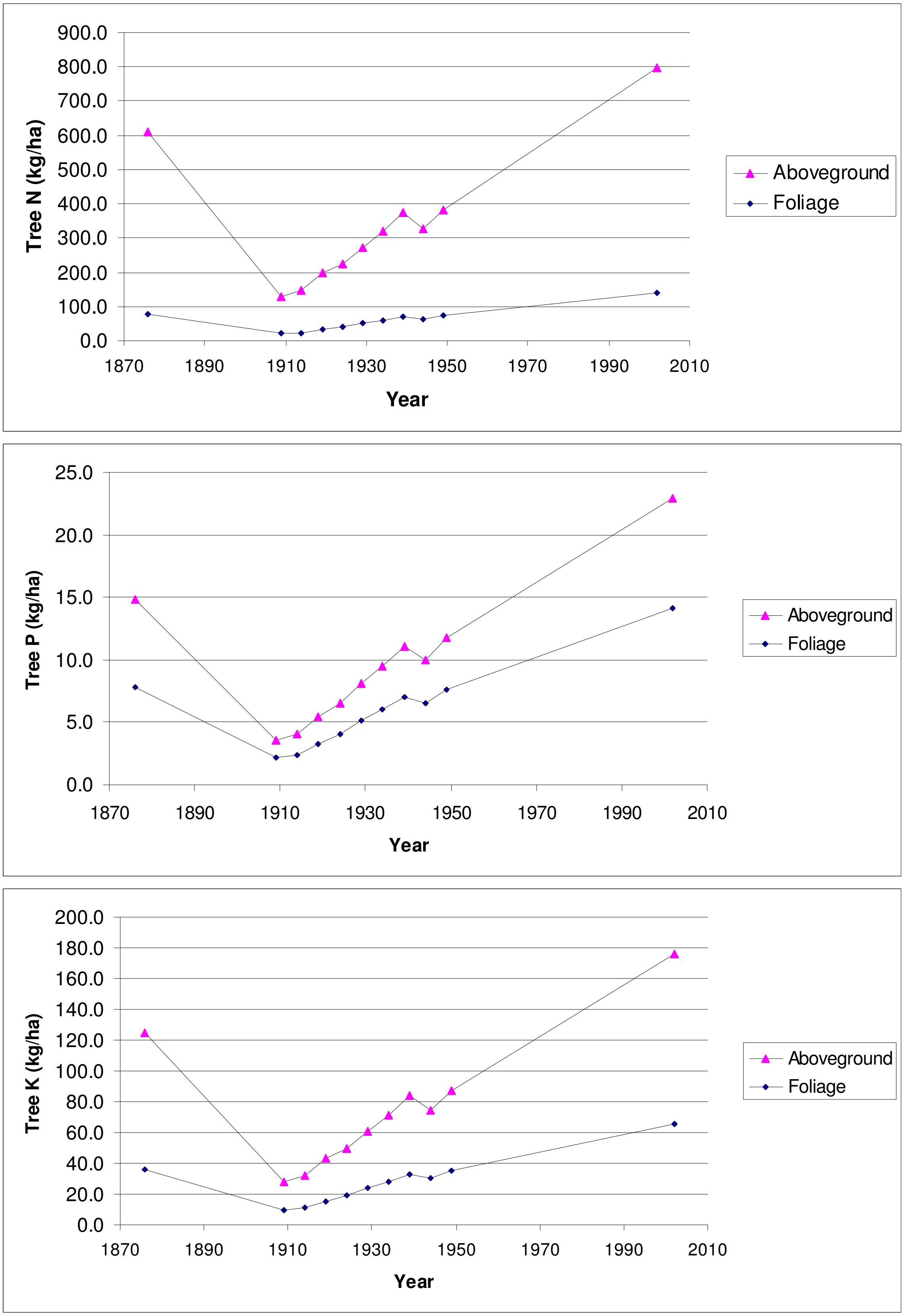

900.0
800.0
700.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
Tree N (kg/ha)
1870
1890
1910
1930
1950
1970
1990
2010
Year
Aboveground
Foliage
25.0
20.0
15.0
10.0
5.0
0.0
Tree P (kg/ha)
1870
1890
1910
1930
1950
1970
1990
2010
Year
Aboveground
Foliage
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Tree K (kg/ha)
1870
1890
1910
1930
1950
1970
1990
2010
Year
Aboveground
Foliage

Fig. 5.6

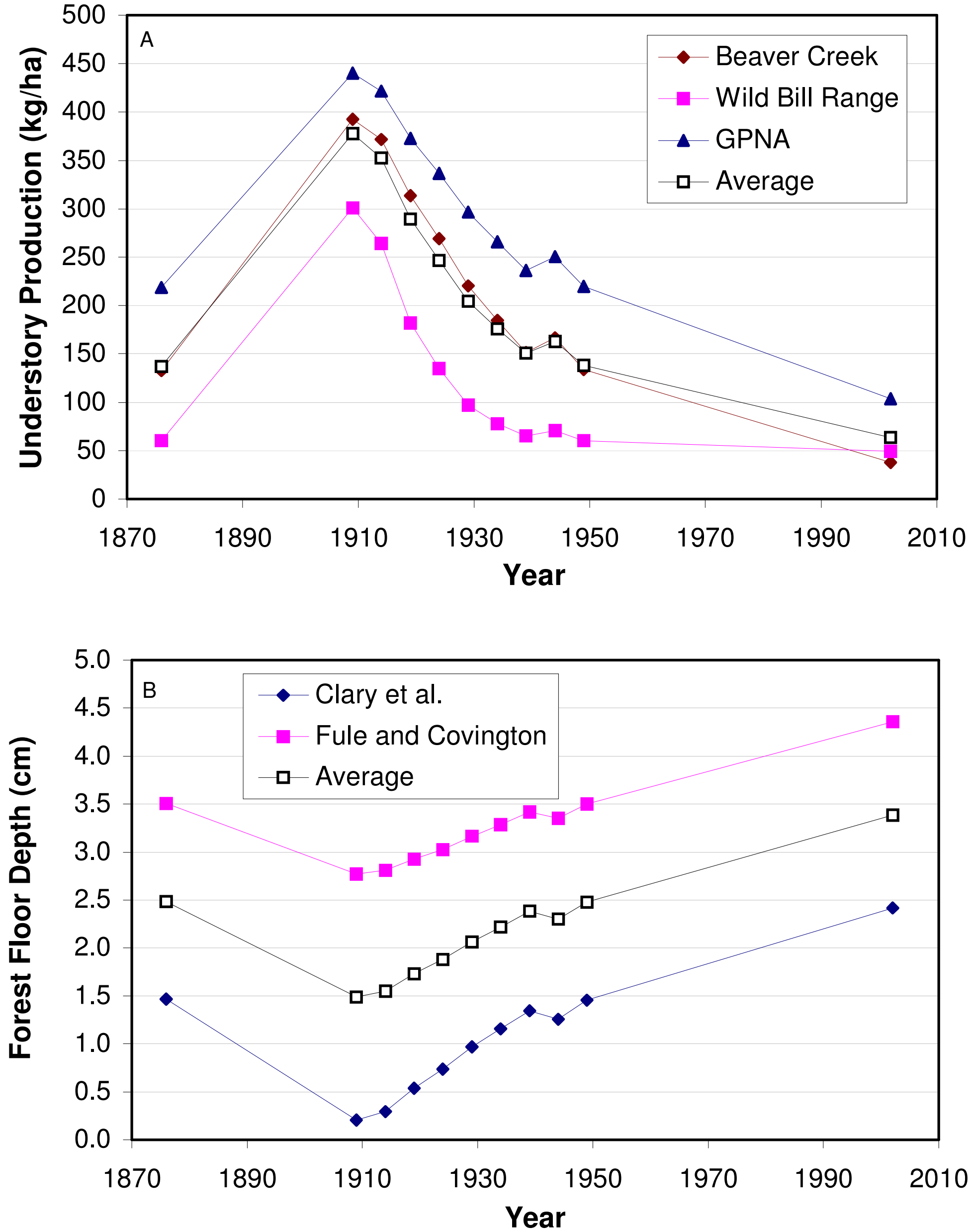

A
Beaver Creek
Wild Bill Range
GPNA
Average
Understory Production (kg/ha)
Year
B
Clary et al.
Fule and Covington
Average
Forest Floor Depth (cm)
Year

Fig. 5.7

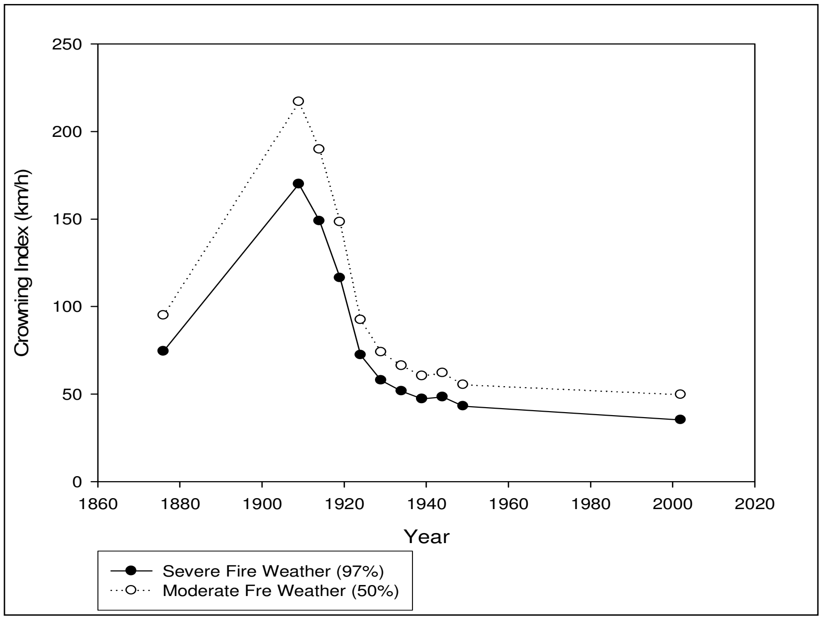

250
200
150
100
50
0
Crowning Index (km/h)
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year
Severe Fire Weather (97%)
Moderate Fre Weather (50%)

Fig. 5.8

Table 5.1. Equations used to predict component biomass of ponderosa pine trees on COCS1A. Table shows dependent variable (Y), y-transformation, (Y-transf.), regression coefficients (a, b), X variable transformation (X-transf.), correction factor (CF), sample size (N), diameter range of sample (range; cm), r-squared values for regression (r-squared), and reference.

Y	Y-Transf.	a	b	X-Transf.	CF[1]	N	range	r-squared	reference
Stemwood (kg)	Ln	-4.12789	2.703856	Ln	1.046872	26	15.5-80.8	0.956	Covington, Fulé, Hart *unpublished;* Gholz 1979
Bark (kg)	Ln	-4.22913	2.269097	Ln	1.030426	26	15.5-80.8	0.959	Covington, Fulé, Hart *unpublished;* Gholz 1979
Live branches[2] (kg)	Ln	-6.02777	2.865545	Ln	1.042516	26	15.5-80.8	0.964	Covington, Fulé, Hart *unpublished;* Gholz 1979
Foliage (kg)	Ln	-4.13171	2.015898	Ln	1.067169	26	15.5-80.8	0.896	Covington, Fulé, Hart *unpublished;* Gholz 1979
Coarse roots[3] (kg)	N/A	0.00104	3.085	N/A	N/A	42	18.3-67.6	0.766	Omdal et al. 2001
Fascicle (g)	N/A	0.1111	0.00514	NA	NA	20	2.5-50.8	N/A[4]	Cable 1958

[1] Correction factor for log-bias
[2] Includes bark
[3] Equation of the form $Y = a(X)^b$; where Y = coarse root weight and X = tree diameter
[4] No r-squared given; standard error of estimate for equation = 0.1511

Table 5.2. Nitrogen (N), phosphorus (P), and potassium (K) percentages in aboveground biomass components of ponderosa pine trees (Clayton and Kennedy 1980).

	Percentage of component biomass		
Component	N	P	K
Foliage	1.550	0.159	0.739
Branches[1]	0.585	0.019	0.130
Stem bark	0.621	0.016	0.137
Stem wood	0.342	0.000[2]	0.042

[1] Includes bark
[2] Below detectable limits of analysis (Clayton and Kennedy 1980)

Table 5.3. Equations used to predict crown radius (m), understory production (kg/ha), and forest floor depth (cm) on COCS1A. All equations use basal area (m^2/ha) as the independent variable except for crown radius, which uses tree diameter (cm), and Clary et al.'s (1968) forest floor depth, which uses the average understory production (kg/ha) shown in Fig. 5.6a. The equation provided by Jameson (1967) has been re-expressed in metric units and the equation provided by Clary et al. (1968) has been reversed and re-expressed in metric units.

Y	Equation	N	location	Range of X	r^2	Reference
Crown radius	$Y = \left(0.2496 + 0.2110\sqrt{X}\right)^2$	2287	Fort Valley (this study)		0.820	A.J. Sánchez Meador, unpublished data
Herbaceous biomass	$Y = \left(27.806813 - 2.8385927\sqrt{X}\right)^2$	55	Gus Pearson Natural Area	0-101.8	0.628	Casey and Moore, 2004, unpublished data
Total herbage production	$Y = 10^{(2.773 - 0.0309X)}$	--[a]	Beaver Creek watershed; clay loam soils	--[b]	0.854	Bojorquez-Tapia et al. 1990
Total herbage production	$Y = 752.7616 - 703.4737\left(1 - e^{-0.011019X}\right)^{5/4}$	21[c]	Wild Bill Range	0-45.9	--	Jameson 1967
Forest floor depth[d]	$Y = 7.4305 - 2.8578(\log(X/1.1209))$	228	Beaver Creek	11.2-336.5	0.58	Clary et al. 1968
Forest floor depth	$Y = 2.49 + 0.0484X$	100[e]	Northern Arizona	--[f]	0.620	Fulé and Covington 1994

[a] exact sample size unclear; 50 to 515 plots were measured each year between 1959 and 1980 and analysis was based on the average annual production of each plot
[b] range of X not reported
[c] each point represents the mean of between 2 and 30 0.9 m^2 plots
[d] combined total of litter (L), duff (F), and humus (H) layers
[e] 33 plots from the North Rim of Grand Canyon National Park, 11 plots from the Bar M watershed, and 56 plots from the Gus Pearson Natural Area
[f] range of X not reported; mean basal area = 52.6 m2/ha; SE = 4.52 m^2/ha

Table 5.4. The 50th and 97th percentiles for fuel moisture, wind, and temperature for the Flagstaff Weather Station in June, 1968-2003.

	June	
Variable	**50th percentile**	**97th percentile**
1 H moisture (percent)	5	2
10 H moisture (percent)	6	3
100 H moisture (percent)	8	4
1000 H moisture (percent)	11	6
Wind speed (mph)	12	25
Temperature (°F)	79	91

<u>Objective 6</u>: Spatial pattern changes from 1909 to 2002: A Case study of COCS1A

By: M. M. Moore, A. J. Sánchez Meador, and J. D. Bakker

Introduction:

Few studies have examined the spatial patterns of ponderosa pine in northern Arizona. Pearson (1910) was the first to mention that ponderosa pine, particularly the regeneration, is not uniform, but rather occurs in groups. Cooper (1960) attempted to quantify the spatial structure in ponderosa pine on the White Mountain Apache Reservation. He used contiguous quadrats and found that the trees were aggregated into distinct groups that ranged from 0.06 to 0.14 ha (0.15 to 0.35 ac), and that tree reproduction established in groups of about the same size in the interspaces. Cooper (1961) used Clark and Evans' R to examine tree aggregation and the effect of spacing on growth of individual pine trees. He discussed four scales of patterns in ponderosa pine forests from the individual and small groups of trees to the stand-level patterns. Cooper (1961) concluded that trees in younger stands (around 40 years) had a tendency to aggregate and that trees in older stands (around 80 years) had a tendency to be more regularly distributed. However, this result was mixed, and many of the results were not statistically significant. White (1985) examined ponderosa pine presettlement tree patterns (live trees ≥ 106 yrs) in the Gus Pearson Natural Area, an unharvested stand <1 km from COCS1A. He used Clark and Evans' R to determine that stems of these older trees were strongly aggregated and that most occurred in groups of three or more trees (3 to 44 stems) occupying areas ranging from 0.02 to 0.29 ha. The focus of White (1985) was to examine the even- or uneven-agedness of these older tree groups. Biondi et al. (1994) used variograms and kriged maps to examine the spatial structure of stem diameter (DBH), basal area, and basal area increment in the Gus Pearson Natural Area. They found that stem size was spatially autocorrelated over distances up to 30 m, which they interpreted as a measure of average patch diameter. They also concluded that because patch diameter remained constant though time, the observed increase in tree density was due to an increased number of patches, not to an areal increase of existing patches.

We examined the spatial patterns of trees on one plot, COCS1A (Fig. 1.2, and Fig. 6.1; 6.4 ac, 2.59 ha, 160 x 160 m) at plot establishment (1909 unharvested [reconstructed structure as it would have been if harvesting had not occurred in 1894]; Sánchez Meador unpublished data; and 1909 harvested [actual structure post-harvest]) and in contemporary times (2001-2002). We refer to these three scenarios as 'Reconstructed-Establishment', Actual-Establishment', and 'Actual-Contemporary', respectively. Forest structural conditions in Actual-Establishment in 1909 and Actual-Contemporary in 2002 are described in Objective 5.

Spatial Statistics Background and Analysis:

Point pattern and surface pattern analyses were conducted on live trees ≥ 9.14 cm DBH. We describe each spatial statistic and analysis in the following paragraphs. All analyses were conducted using the S+SpatialStats module (MathSoft 2000), a spatial analysis library (Reich and Davis 2003) developed for S-Plus (Version 6.1; Insightful Corporation 2002), and spatial correlation software developed by Richard Duncan (Duncan and Stewart 1991).

Point pattern analyses explore the mapped positions of points (stems of live trees in our case) on a plane using "plot-less sampling" and determine whether the spatial distribution of the trees is random (also called complete spatial randomness or CSR), clumped (also called aggregated), or uniform (also called regular or over dispersed) (Upton and Fingleton 1985, Legendre 1993). The point pattern techniques included in this report include two nearest-neighbor distance (NND) indices (Clark and Evans' R [Clark and Evans 1954] and Pielou's Index [Pielou 1959, Pielou 1977]). Values of Clark and Evans' R < 1 indicate an aggregated distribution, values > 1 indicate a uniform distribution, and R = 1 indicates a random distribution. Pielou's Index is interpreted as the inverse of Clark and Evans' R (i.e., values < 1 indicate uniform distribution and values > 1 indicate an aggregated distribution). These two measures also differ in that Clark and Evans' R examines the distribution associated with distance from a random tree to its nearest neighbor, while Pielou's Index examines the squared distance from a randomly generated point to the nearest tree. We used 100 random points for 1909 data and 1000 random points for 2002 data for Pielou's Index. Both NND indices were corrected for edge effects. For each NND index, a z-test was used to determine whether the spatial distribution was significantly ($\alpha = 0.05$) non-random.

One of the major problems of NND indices is that they convey whether vegetation is clumped, uniform, or random, but they do not give any information on the size or spacing of the clumps involved in the pattern (Dale et al. 2002). According to Pielou (1977), Clark and Evans R is related to the intensity of the pattern, while Pielou's index is related not only to the intensity and but also to the grain. Neither index provides information about scale.

The third point pattern technique included in this study was Ripley's K(t) statistic (Ripley 1976, Ripley 1977). This is a second-order statistic related to plant-to-all-plant techniques (Dale 1999) based on distances between pairs of points (live trees) and the number of points within a certain radial distance (t) of each point. We reduced the error induced by edge effects in this analysis by using a maximum distance of 80 m (half of the minimum dimension of the plot; Boots and Getis 1988). Visual interpretation is simplified using a variance stabilizing transformation of K(t) to L(t)-t. The graphs of L(t) resemble a correlogram; values >0 indicate clumped and values <0 indicate uniform spatial distributions. To test for significance of the L(t) observed values, a Monte Carlo approach was used where the observed results were compared with the frequency distribution from 100 random trials, therefore, the confidence limits are set at $\alpha = 0.01$ (Upton and Fingleton 1985). Ripley's L(t) distribution is the cumulative frequency distribution of observations at each point-to-point distance; because it preserves distances, it can quantify intensity of pattern at multiple scales (Upton and Fingleton 1985, Dale 1999).

As mentioned above, point pattern indices examine the distribution of points (trees) across space, but oftentimes we are interested in characterizing variation in a continuous variable (e.g., tree size, growth rates, heights) as a function of position in a geographic area. Surface pattern analysis is a broad area of statistics that, in general, describes the spatial structure of a variable and tests for the presence of spatial dependence (autocorrelation; the tendency of a variable to be correlated with itself at finite distances) (Rossi et al. 1992, Legendre and Legendre 1998). We used the univariate structure functions of autocorrelation (as a correlogram) and semivariance (as a variogram) to quantify the spatial dependence of individual tree basal area (cross-sectional area of the stem at breast height; m^2) on COCS1A. A 1 m lag distance (the geographic distance between two samples) and an 80 m maximum lag distance (half of the smallest plot dimension) was used in all statistical tests described below. For more information on the conceptual and mathematical relationships between these spatial analysis methods, the reader is referred to Legendre (1993), Dale (1999), and Dale et al. (2002).

Spatial autocorrelation in a variable is basically derived and behaves in the same way as the familiar correlation coefficient, whereby some index of covariance is computed for a series of lag distances. We used Moran's I (Moran 1950, Legendre and Legendre 1998) as the index of covariance in this study. A correlogram is a plot of the correlation coefficient (Moran's I) against lag distance; I ranges from +1 (perfect positive spatial correlation) to -1 (perfect negative spatial correlation); 0 indicates no spatial correlation. Each correlogram was tested for global significance; individual autocorrelation statistics ($\alpha = 0.05$, Bonferroni corrected to account for number of distance classes) were tested only if the global test was significant (Legendre and Legendre 1998).

Semivariance examines the spatial variability of an observed variable at each lag distance. The term semivariance means "half of the variance" and is half of the averaged squared difference of all pairs of points separated by a given distance (Rossi et al. 1992). A variogram is a plot of semivariance against lag distance. There is no formal test of significance for a variogram; it simply describes the spatial structure of the data. The key points of interest are the range (the lag distance at which the asymptotic value of the variogram is reached), sill (the semivariance associated with the asymptotic value of the variogram), and nugget (the semivariance when the lag distance is 0).

We used kriging to further aid in data interpretation. Kriging uses the variogram to interpolate or predict the variable of interest at points not measured originally. We set the pixel size to 5x5 m for all kriged maps. In these maps, individual tree basal area is interpolated across the site and shading is used to indicate areas where individual trees have high basal area or low basal area. Contours are drawn to delineate areas with uniform individual tree basal areas, and thus, closer contours contain the greatest variation in individual tree basal area.

Results:

Both nearest-neighbor indices indicate that live trees ≥ 9.14 cm DBH were clumped (aggregated) on COCS1A at plot establishment in 1909 (both reconstructed and actual) as well as in 2002. Clark and Evans' R showed a stronger tendency of trees to clump ($R = 0.58$; $p = 0.0$) and a smaller average distance to the nearest neighbor (4.1 m) in 1909-actual as compared to 1909-reconstructed ($R = 0.82$; $p = 0.0$; distance to nearest neighbor = 4.5 m). Contemporary patterns (2002) also exhibited clumpiness, but the tendency for trees to aggregate was not as strong ($R = 0.91$; $p = 0.0$) and the average distance to the nearest neighbor was much smaller (1.9 m) than in 1909.

Pielou's Index also indicates that the spatial arrangement of trees was significantly clumped ($p = 0.0$) under all three scenarios. Trees were more clumped in plot establishment 1909-actual than in plot establishment-reconstructed (Pielou's Index = 2.73 and 2.18, respectively). Contemporary patterns (2002) were still clumped but the strength of the aggregation was diminished (Pielou's Index = 1.51) compared to both 1909 scenarios.

Ripley's K indicated that although spatial patterns were present in all three scenarios, the trends differed. In both 1909 scenarios, there was a distinct peak in aggregation of trees from 7.0 to 8.5 m (Fig. 6.2a, 6.2b). This peak indicated that clumps of trees were approximately 0.02 ha in size; the fact that the lag distance of the peak changed little indicates that the size of these clumps was minimally affected by the harvest. However, the height of this peak was much larger for plot establishment-actual than for reconstructed, suggesting that the 1894 harvest increased the aggregation of the residual trees. In 1909-reconstructed, trees were aggregated to about 34 m and uniformly distributed beyond about 53 m (Fig. 6.2a). Clumps of trees were more than 80 m apart (i.e., there were no additional significant positive L(t) values out to the maximum distance tested). In 1909-actual, however, trees were clumped at all spatial scales up to the maximum distance tested (Fig. 6.2b), indicating that harvesting increased the clumpiness of trees. In 2002, the trees remain clumped at all spatial scales up to the maximum distance tested (Fig. 6.2c), although the distinct small (0.02 ha) clumps from 1909 are no longer apparent.

Global tests of Moran's I indicated that trees were spatially autocorrelated on the basis of individual tree basal area in all three scenarios (p = 0.026, 0.011, and 0.000 for reconstructed-1909, actual-1909, and actual-2002, respectively), meaning that smaller trees are more likely to be near one another and larger trees are more likely to be near one another than expected by chance alone. Bonferroni corrected individual autocorrelation statistics, however, were significant only at the fine scale (up to 15 m) in reconstructed-1909 scenario, and only at 5 m in the actual-1909, but were significant in contemporary-2002 across most lags until 80 m (Fig. 6.3). In 2002, spatial autocorrelation (clumps of similar sized trees) extended to about 17 m and then dropped to 0, suggesting that there was no spatial structure between tree basal area and distance after that point (Fig. 6.3c).

Variogram results and parameter estimates (range, sill, nugget) for individual tree basal area (m^2) on COCS1A for 1909 (reconstructed and actual) and 2002 are shown in Figure 6.4. Trees were spatially autocorrelated up to 27.9 m in reconstructed-1909, and up to 34.4 and 34.7 m, respectively in actual-1909 and actual-2002. The high partial sill in 1909-reconstructed reflects the much higher variation in this data set (Fig.6.4a) than in actual-1909 (Fig. 6.4b) or 2002 (Fig. 6.4c). The nugget (unresolved variation at very fine scales) was similar for all three scenarios.

Kriged maps illustrated the spatial pattern of individual tree basal area across the plot (Fig. 6.5). Lighter shading indicates areas with larger trees and closer contours indicated areas with greater variation in individual tree basal area. Individual tree basal area was much more variable in reconstructed-1909 (Fig. 6.5a) than in actual-1909 (Fig. 6.5b), indicating that the 1894 harvest reduced the variation in basal area. In 2002, values ranged from very low individual tree basal area (small trees; darker shading) to larger individual tree basal areas (larger trees; lighter shading) (Fig. 6.5c). The areas of largest individual tree basal area differ between all three scenarios. The total basal area on the site cannot be calculated directly from these maps as it is a function of both the individual tree basal area and the number of trees per hectare.

Discussion:

Our results quantify the notion that ponderosa pine stands of northern Arizona have become more spatially homogeneous since the early 1900s. The differences between the historical and contemporary data sets are pronounced. Historically, this site exhibited dense clumps of trees averaging 0.02 ha in size alternating with sparsely populated zones or interspaces between clumps (Fig. 6.2a,b). In contrast, the pattern in 2002 was characterized by clumps that span large areas (Fig. 6.2c). Tree density has greatly increased over the last 90+ years (Objective 5; Moore et al. 2004) and it is thought that the majority of tree recruitment has occurred in the shade of existing trees (Pearson 1910) and in the interspaces (available growing space) between existing clumps. Pielou (1977) suggests that this is also a shift from high-intensity, fine-grained pattern to one of low-intensity and coarse-grained pattern.

The partial harvest in 1894 homogenized the plot with respect to tree size by removing many of the largest diameter trees and changing the amount and distribution of tree sizes across the plot. However, the spatial effects of the partial harvest in 1894 varied with the scale of consideration. At fine scales, the size of clumps was largely unaffected (Fig. 6.2a, 6.2b). At coarser scales, the clumpiness of the residual trees was increased because the harvest removed all of the trees in large patches (e.g., north-central, central, and southwest areas of Fig. 6.1b). This is also reflected by Clark and Evans' R, which resulted in higher aggregation for 1909-actual than 1909-reconstructed (R = 0.58 and 0.82, respectively).

Individual autocorrelation statistics were significant at small lag distances, which suggest a positive spatial relationship and a greater chance of trees of similar sizes occurring together at fine-scales in both reconstructed-1909 and actual-1909 (Fig. 6.3a,b). This spatial relationship of tree size and small lag distances held true up to 15 m and 5 m for the reconstructed-1909 and actual-1909 scenarios, respectively. This result suggests that the late 1800s harvest on this plot changed the spatial pattern by grouping similar sized trees into smaller groups (from 0-15 m pre-harvest to 0-5 m post-harvest). The correlogram was also significant in contemporary-2002 up to 25-30 m, increasing the patch or clump size of trees since the early 1900s. Undoubtedly, the doubling or tripling of patch size over the last 90+ years is due to the large recruitment of trees during this time period (Biondi 1996, Savage et al. 1996).

The semivariogram showed a similar pattern, increasing variance with increasing distance out to 28-35 m (Fig. 6.4), indicating that there is a spatial pattern associated with tree size. The range changed remarkably little between 1909 and 2002, however, particularly in light of the 10-fold increase in tree density (Objective 5).

Spatial pattern results from this study on COCS1A are similar to the studies cited in the Introduction above. For example, the range changed relatively little between 1909 and 2002 (Fig. 6.4) and the magnitude of aggregation has declined (Clark and Evans' R). However, we found that trees were aggregated prior to harvest and that harvesting amplified the clumpy nature of ponderosa pine. This aggregation has continued to contemporary times (2002) but the aggregation is due to several factors including the late 1800s tree harvest selection patterns and the establishment patterns of the large pine regeneration pulses during the 1900s.

Summary:

The spatial pattern differences between the historical (reconstructed-1909 and actual-1909) and contemporary (2002) data sets on COCS1A are pronounced. Historically, this site exhibited dense clumps of trees averaging 0.02 ha in size alternating with sparsely populated zones or interspaces between clumps. In contrast, the pattern in 2002 was characterized by clumps that span large areas with few interspaces. The partial harvest in 1894 homogenized the plot with respect to tree size by removing many of the largest diameter trees and changing the amount and distribution of tree sizes across the plot. However, the spatial effects of the partial harvest in 1894 varied with the scale of consideration. At fine scales, the size of clumps was largely unaffected by harvesting; a coarser scales, the clumpy nature of the residual trees was increased because the harvest removed all of the trees in large patches.

List of Figures for Objective 6.

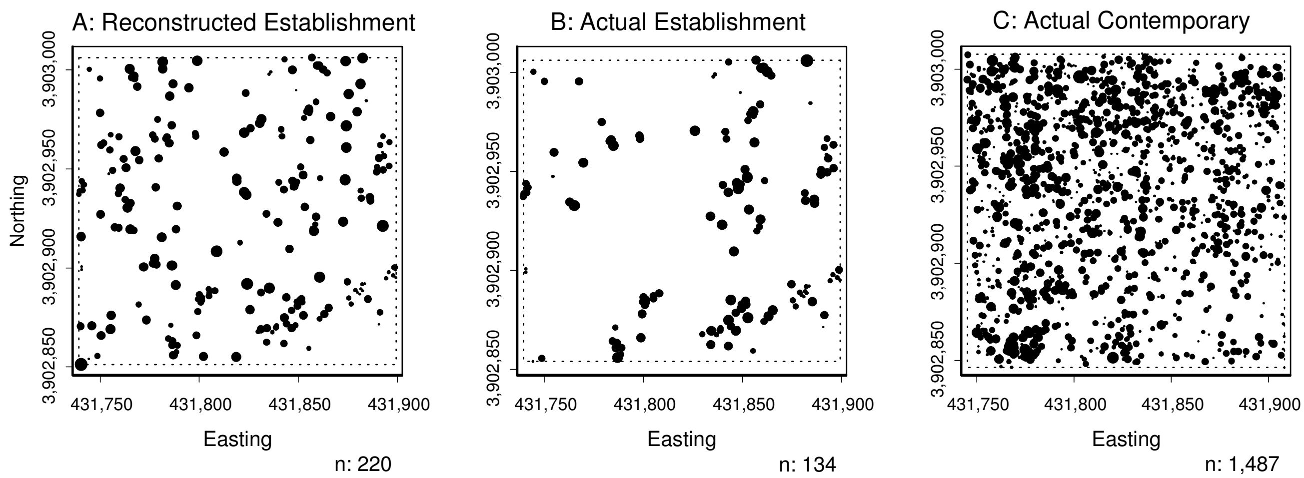

A: Reconstructed Establishment
B: Actual Establishment
C: Actual Contemporary
Northing
3,903,000
3,902,950
3,902,900
3,902,850
431,750
431,800
431,850
431,900
Easting
n: 220
n: 134
n: 1,487

Fig. 6.1

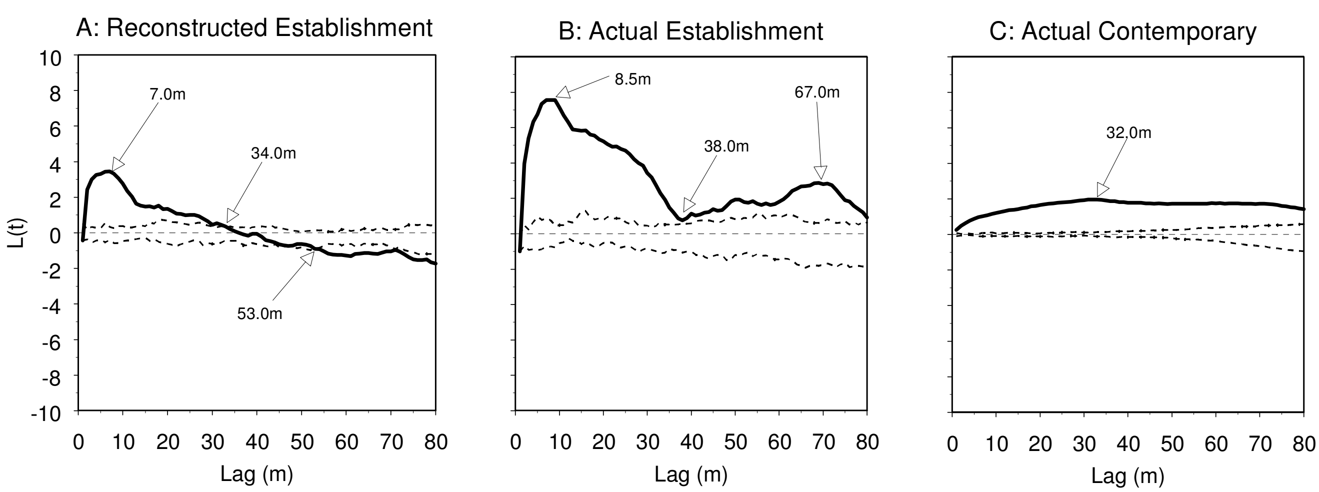

A: Reconstructed Establishment
B: Actual Establishment
C: Actual Contemporary
L(t)
Lag (m)
7.0m
34.0m
53.0m
8.5m
38.0m
67.0m
32.0m

Fig. 6.2

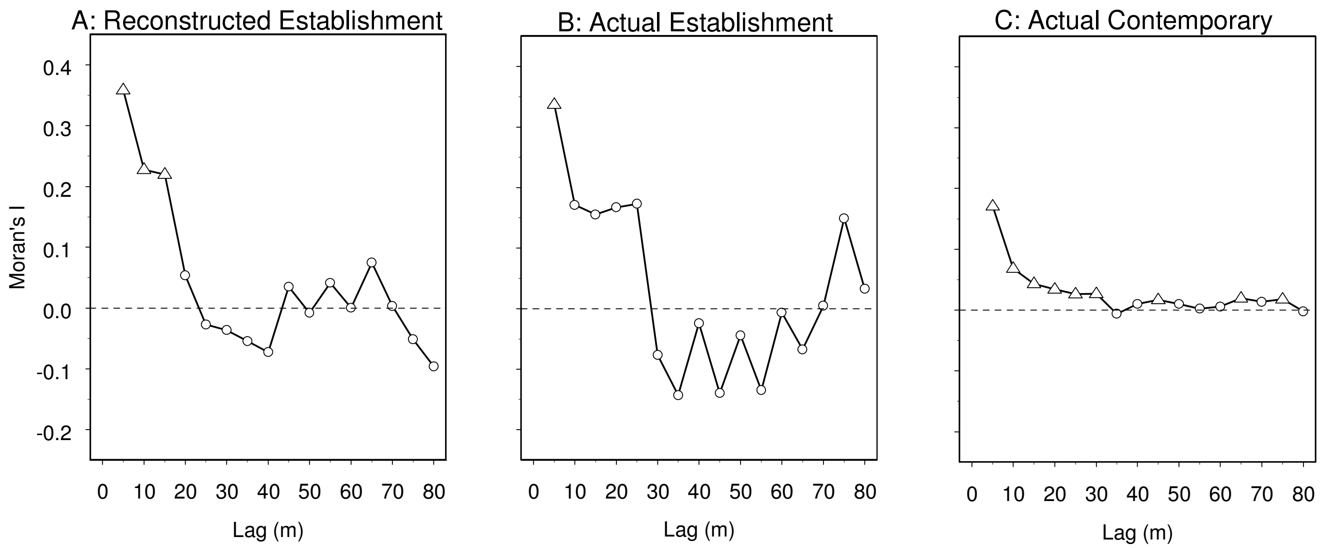

A: Reconstructed Establishment
B: Actual Establishment
C: Actual Contemporary
Moran's I
Lag (m)

Fig. 6.3

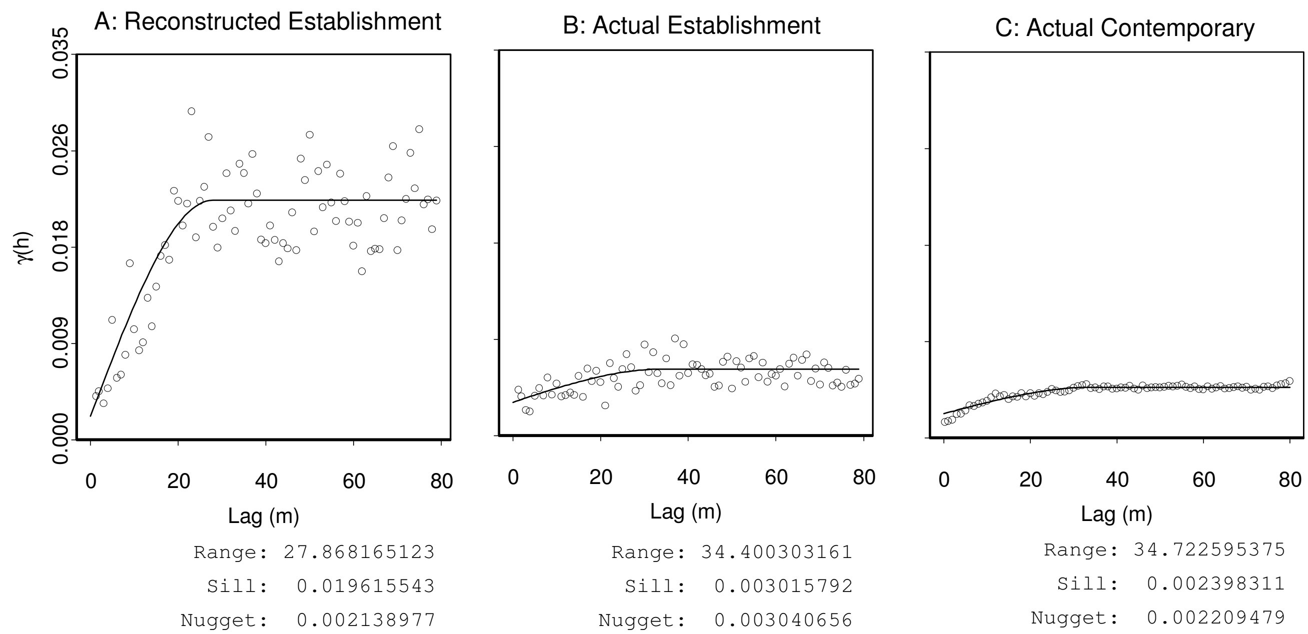

A: Reconstructed Establishment
B: Actual Establishment
C: Actual Contemporary
γ(h)
Lag (m)
Range: 27.868165123
Sill: 0.019615543
Nugget: 0.002138977
Range: 34.400303161
Sill: 0.003015792
Nugget: 0.003040656
Range: 34.722595375
Sill: 0.002398311
Nugget: 0.002209479

Fig. 6.4

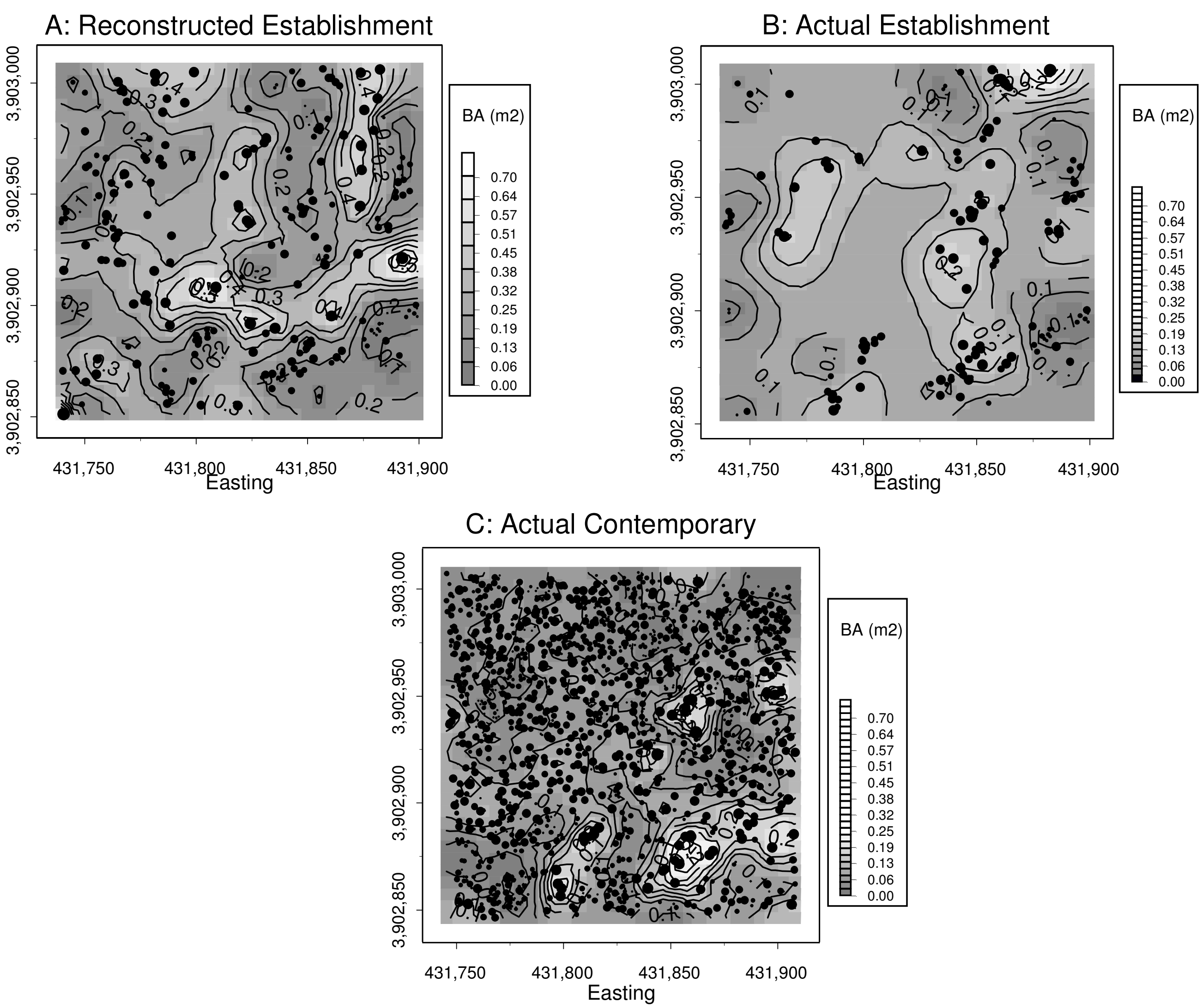

A: Reconstructed Establishment
B: Actual Establishment
C: Actual Contemporary
BA (m2)
0.70
0.64
0.57
0.51
0.45
0.38
0.32
0.25
0.19
0.13
0.06
0.00
3,903,000
3,902,950
3,902,900
3,902,850
431,750
431,800
431,850
431,900
Easting

Fig. 6.5.

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