Abstract—Dendroecological forest reconstruction techniques are used to estimate presettlement structure of northern Arizona ponderosa pine forests. To test the accuracy of these techniques, we remeasured 10 of the oldest forest plots in Arizona, a subset of 51 historical plots established throughout the region from 1909 to 1913, and compared reconstruction outputs to historical data collected. Results of this analysis revealed several distinct sources of error: (1) After about 90 years, 94 percent of the recorded trees were relocated and remeasured, but approximately three trees/ha were missing in the field due to obliteration by fire or decay; (2) sizes of trees living in 1909 were overestimated by an average of 11.9 percent; (3) snag and log decomposition models tended to underestimate time since tree death by an undetermined amount; and (4) historical sizes of cut trees were difficult to estimate due to uncertainties concerning harvest dates. The aggregate effect of these errors was to overestimate the number of trees occurring in 1909–1913. Sensitivity analysis applied to decomposition equations showed variations in reconstructed sizes of snags and logs by ±7 percent and stand density estimates by 7 percent. Results suggest that these reconstruction techniques are robust but tend to overestimate tree size and forest density.

Introduction

Ponderosa pine (Pinus ponderosa Douglas ex P. Lawson & Lawson) forest ecosystems in northern Arizona have undergone dramatic physiognomic changes over the past 120 years (Covington and Moore 1994a; Covington and others 1997; Fule and others 1997). Logging, fire suppression, and overgrazing in the latter part of the 19th century created conditions suitable for a population explosion of pine regeneration. Open parklike stands, maintained by frequent surface fires prior to Euro-American settlement (about 1876), of the region, have been replaced by closed canopied forests with resulting deleterious effects on biological diversity and ecological function (Covington and Moore 1994a). Associated biomass accumulation and the development of fuel ladders represent extreme fire hazards and expose these forests to an increased potential for stand-replacing crown fires. Restoration of ecological processes and structure holds promise for reestablishing indigenous levels of biological diversity and ecological function in northern Arizona ponderosa pine forests (Covington and Moore 1994b; Covington and others 1997).

Treatments designed to restore ponderosa pine ecosystems are based on an understanding of presettlement structural and compositional characteristics that are collectively known as reference conditions. Forest reconstruction is one tool used to estimate reference conditions. Techniques for reconstruction include dendrochronological measurement of fire scars and increment cores from stumps, logs, and standing trees, direct measurement of remnant woody evidence, and backwards radial growth modeling (Fule and others 1997). Forest structural information generated by reconstruction includes past diameter distribution and stand density estimates. The precision of these analyses is highly dependent on field identification of pre-settlement evidence, dendrochronological proficiency, and relationships utilized in “reverse” growth and decay modeling. Our objective in this study was to use data from historically measured forest plots to test the precision of our forest reconstruction techniques. Specifically, we wanted to (1) test our ability to identify historically measured trees in the field, (2) compare reconstruction model outputs such as stand density and tree sizes to historical data, and (3) identify key sources of error associated with the reconstruction process.

Background

Between 1909 and 1913, a series of 51 permanent plots were established within the ponderosa vegetation type throughout Arizona and New Mexico (Woolsey 1911, 1912). The purpose of these plots was to increase understanding of western yellow pine (now ponderosa) growth, regeneration, and management. These are the oldest known ponderosa pine sample plots in the Southwest. Plots of around 1 to 6 ha (2 to 14 acres) were established on areas where up to two-thirds of the standing overstory volume had recently been harvested. The permanently marked plots were subdivided into 20 m (66 ft) grids wherein all trees greater than 10.16 cm (4 inches) in diameter at breast height (d.b.h.) (1.4 m) were mapped. Measurements for these trees included d.b.h.,
height, vigor, and age class. The USDA Forest Service remeasured these plots every 5 years until the studies were abandoned around 1934–1939. In the mid-1990s, we began to uncover the historical data and maps associated with the “Woolsey” plots. In 1996, we initiated a project to relocate and remeasure as many of the historic plots as possible. By 2000, we had remeasured and applied reconstruction analysis to 15 plots. This paper describes the results of analysis of 10 plots located near Flagstaff, Arizona.

Methods

Study Area

The 10 historical plots used in this study are within a 24-km radius of Flagstaff (35°8'N latitude, 111°40'W longitude), Arizona, on the Coconino National Forest (fig. 1). Elevation at the sites ranged from around 2,100 to 2,200 m. Average annual precipitation in the area is 50.3 cm with about half falling in winter as snow and the other as rain associated with a mid-summer monsoon pattern. Mean annual temperature is 7.5 °C. The soil of the area is a stony clay loam of basalt derivation.

Ponderosa pine is the dominant overstory species of the area often occurring in pure stands or mixed with Gambel oak (Quercus gambelii Nutt.). Important understory species include grasses, Festuca arizonica Vasey, Muhlenbergia montana (Nutt.) Hitchc., Bled扒haronourn tricholepis (Torr.) Nash, and Sitanion hystrix (Nutt.) J.G. Smith, and forbs, Achillea millefolium var. occidentalis D.C., Pseudocymopterus montanus (Gray) Coul. & Rose, Erigeron divergens Torr & Gray, and Potentilla crinita Gray. Shrubs are not common but include scattered populations of Ceanothus fendleri Gray and Rosa woodsii Lindl.

Remeasurement of Historical Plots

The 10 plots, originally established in 1909 (eight plots) and 1913 (two plots) were remeasured in 1997–1999. We used copies of the stem maps drawn in 1915 to relocate plot corners and grid intersections. Although the historical plots ranged in size, we standardized our methods to remeasure subplots of 1.02 ha (2.5 acres), systematically originating from the northwest corners of the original plots. After consulting historical maps to determine plot orientation, we used a transit, staff compass, and tape to reestablish the original grid system as truly as possible. Subplots consisted of 25 grid cells of approximately 404 m² each. After subplots were established, 1915 maps were not referenced again until after remeasurement had been completed. Due to the size of the subplots, results presented here are interpreted in terms of trees per hectare.

Grid cells within subplots were thoroughly searched and all structures equal to or greater than 1.4 m in height, either presently or at some past time, were numbered and tagged. Tree structures included live trees, snags, logs, stumps, and stump holes. Diameter at breast height (d.b.h.; measured at 1.4 m above the ground) and/or diameter at stump height (d.s.h.; measured at 40 cm), total tree height, condition class (1–9), and age class (preplot, "preplot," or postsettlement; see below) were recorded for all tree structures. For stump holes, d.s.h. was estimated. Tree condition classes followed a classification system commonly used in ponderosa pine forests (Maser and others 1979; Thomas and others 1979). The nine classes were as follows: (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, and (9) cut stump.

In the field, age classifications were based on tree size and bark characteristics and then verified when possible in the laboratory. Tree ages were grouped in the field into three categories: preplot, preplot, and postplot. Structures greater than 37.5 cm d.b.h., clearly yellow-barked, or dead, large, and highly decayed, were presumed to be greater than 100 years old (White 1988) and classified as preplot in age. We classified trees as "preplot-aged" (in other words, established prior to historical plot measurement) if they did not meet preplot classification criteria (for example, did not have yellow bark) but were larger than a predetermined size. Preplot size was determined for individual subplots by measuring diameter and field aging a sample (10) of nearby trees. Ponderosa pine with bark appearing transitional in age between yellow barked and black barked trees were located just outside the subplot boundaries and bored at 40 cm. Ring counts were made and the results were compared with the plot establishment date. The average diameter of trees within 10 years of the plot establishment date was used as the preplot size cutoff. Live trees of this size or larger without yellow bark were classified as preplot-aged. In some cases, preplot size was not different than preplot (37.5 cm at d.b.h.) and classification was made based on bark characteristics. Trees with black bark and smaller than the minimum preplot and preplot diameters were classified as postplot.

Diameter at stump height and crown radius (average of two measurements) was measured for all preplot and preplot ponderosa pine trees. For species other than ponderosa pine, d.s.h. was measured on all trees. Increment cores were collected at 40 cm for all trees greater than 37.5 cm d.b.h. and for oak and juniper species greater than 17 cm. Additionally, increment cores were collected and d.s.h. and
crown radius was measured for a 20 percent random sub-
sample of live postplot (all species) trees. Increment cores
were stored in paper straws until denrochronological anal-
ysis could be done in the laboratory. Dendrochronological
analysis involved cross-dating cores (Stokes and Smiley
1987) against known annual ring patterns (Graybill 1987)
and measuring radial increments from the year prior to core
collection (1997–1999) to the year of plot establishment
(1909–1913). Radial increments to fire exclusion date (1976;
Fule and others 1997) were also measured. Our age classi-
fication scheme was designed to assure that detailed data,
including increment cores, were collected for all trees that
were historically measured or presettlement in age. It also
allowed comparisons to be made regarding changes in age
structure on these plots since establishment.

Analyses

Field Identification of Historical Trees—Historical
trees were identified in the field by noting tree locations
displayed on 1915 maps and examining structures mea-
sured on subplots. Historical trees not measured on subplots
(in other words, missed during remeasurement) were noted
and the error rate was calculated as follows: Error = (number
missed/number on historical map) * 100. A weighted aver-
age for error incorporating all 10 plots was calculated as
follows: Error = (total number missed over all subplots/total
number of historical trees over all subplots) * 100.

Reconstruction Modeling—Field measurements and
increment core data were entered into a computerized stand
reconstruction model (Covington and others, unpublished).
The model applies a series of mathematical functions to field
data in order to estimate tree diameters (d.b.h.) and death
dates for a particular point in time that is defined by the
user. Growth functions employed were gleaned from empiri-
cal growth (Myers 1963) and decay studies (Rogers and
others 1984) of Southwestern ponderosa pine as well as
other species. Sizes of live trees for which increment cores
were collected were reconstructed by subtracting twice the
radial increment from field recorded tree diameters. Sizes of
trees for which no cores were collected or for which core data
were unusable were estimated by applying “reverse” growth
functions. Dead trees were moved backward through decay
classes (Maser and others 1979; Thomas and others 1979)
until an estimated death date was reached, before which
the reverse growth function was applied. Separate equations
were used for blackjack and yellow pine age classes. For cut
trees (stumps) measured in the field, trees were grown in
reverse prior to a cut date that we defined in the model.

For our analyses, we compared stand density and tree
size errors were calculated as follows: Error = (Reconstructed d.b.h. -
Historical d.b.h. / Historical d.b.h.) * 100.

Results

Field Identification of Historical Trees

Nearly all the trees mapped and recorded in 1909 and
1913 were found on the 10 subplots (table 1). The number
of trees missed ranged from 0 to 9 and the overall error rate was
5.7 percent. Historical trees were found in all condition
classes from highly decomposed to live trees still bearing 90-year-old tags. Frequently, missed trees were highly decomposed and little evidence was observable.

A high rate of identification was possible although dense
conditions existed at the time of subplot remeasurement
(1997–1999); there was an average of 1,379 total
structures across the 10 subplots. No clear relationship was
observed between the number of trees missed and the
number that were historically measured. However, the
greatest number of trees were missed on the subplot with the
greatest total number of structures at remeasurement.

Reconstruction Model

Historical Tree Diameter—Diameter reconstruction of
historical trees that were still alive at remeasurement over-
estimated d.b.h. by an average of 11.9 percent (table 2). We
found a slight trend of increased error for smaller trees
(fig. 2). There were no subplots on which tree diameter was
underestimated. Unexpectedly large errors (greater than 60
percent) resulted for diameter reconstruction of unusually
trees fast- or slow-growing trees for which increment data were
available from the historical ledgers. Because data in his-
Table 1—Number of live trees on Woolsey subplots in Arizona at
establishment (1909–1913) and the number missed during

<table>
<thead>
<tr>
<th>Subplot</th>
<th>No. trees on subplot*</th>
<th>No. trees missed</th>
<th>Error percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1A</td>
<td>26</td>
<td>1</td>
<td>3.8</td>
</tr>
<tr>
<td>S1B</td>
<td>25</td>
<td>2</td>
<td>8.0</td>
</tr>
<tr>
<td>S2A</td>
<td>82</td>
<td>5</td>
<td>6.1</td>
</tr>
<tr>
<td>S2B</td>
<td>72</td>
<td>2</td>
<td>2.8</td>
</tr>
<tr>
<td>S3A</td>
<td>47</td>
<td>9</td>
<td>19.1</td>
</tr>
<tr>
<td>S3B</td>
<td>58</td>
<td>2</td>
<td>3.4</td>
</tr>
<tr>
<td>S4A</td>
<td>67</td>
<td>8</td>
<td>9.2</td>
</tr>
<tr>
<td>S4B</td>
<td>61</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>S5A</td>
<td>20</td>
<td>1</td>
<td>5.0</td>
</tr>
<tr>
<td>S5B</td>
<td>83</td>
<td>2</td>
<td>1.2</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>5.7</td>
</tr>
</tbody>
</table>

*Number of historical trees on subplot recorded on 1915 maps.
Overall average = (S No. trees missed / S No. Trees on subplot) * 100.
Error for diameter reconstruction of historical trees that were dead and down at remeasurement averaged -0.6 percent (table 3). Sensitivity analysis showed that dead and down were most accurately reconstructed when moved through decay classes at the 50th percentile rate. Varying decay rate to the 25th percentile slowed movement through decay classes, resulting in earlier estimated death dates and a greater overestimate of historical diameters. Conversely, decay rate set to the 75th percentile sped movement through decay classes, resulting in later estimated death dates and an underestimate of historical diameters. Thus, varying decomposition rates altered size estimates by approximately 7 percent. Due to limited sample sizes for most plots, the overall average was heavily influenced by subplot S2A.

Diameter reconstruction of historical trees that had been cut since original plot establishment (1909–1913) was most accurate when the cut date in the model was set to 1980 (table 4). This was true for every subplot except S4A for which diameter estimates were most accurate when the cut date was set to 1945. Averaged over all subplots, diameter reconstruction of cut trees overestimated d.b.h. at plot establishment by 11.4 percent.

**Tree Density on Subplots**—Overestimation of tree diameter lead to reconstructed tree densities higher than those recorded on historical maps (table 5). Total number of reconstructed trees on subplots represented the sum of (1) historically measured trees, (2) trees historically existing on subplots yet too small (less than 10.16 cm) at plot

---

**Table 2—Errors for reconstruction estimates of historical tree diameters (≥10.16 cm d.b.h.) and number (n) of live trees in analysis.**

<table>
<thead>
<tr>
<th>Plot</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1A</td>
<td>17</td>
</tr>
<tr>
<td>S1B</td>
<td>9</td>
</tr>
<tr>
<td>S2A</td>
<td>29</td>
</tr>
<tr>
<td>S2B</td>
<td>44</td>
</tr>
<tr>
<td>S3A</td>
<td>8</td>
</tr>
<tr>
<td>S3B</td>
<td>29</td>
</tr>
<tr>
<td>S4A</td>
<td>37</td>
</tr>
<tr>
<td>S4B</td>
<td>23</td>
</tr>
<tr>
<td>S5A</td>
<td>14</td>
</tr>
<tr>
<td>S5B</td>
<td>67</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>4.6</strong></td>
</tr>
</tbody>
</table>

*Average weighted by sample size (n).

**Table 3—Error rate (percent) and sample size (in parentheses) for diameter (d.b.h. ≥10.16 cm) reconstruction of historical trees dead and down at time of subplot remeasurement (1997–1999).**

<table>
<thead>
<tr>
<th>Subplot</th>
<th>25th</th>
<th>50th</th>
<th>75th</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1A</td>
<td>40.0</td>
<td>26.8</td>
<td>(2)</td>
</tr>
<tr>
<td>S1B</td>
<td>-2.1</td>
<td>-10.2</td>
<td>(2)</td>
</tr>
<tr>
<td>S2A</td>
<td>-25.2</td>
<td>-26.3</td>
<td>(28)</td>
</tr>
<tr>
<td>S2B</td>
<td>31.6</td>
<td>11.1</td>
<td>(6)</td>
</tr>
<tr>
<td>S3A</td>
<td>40.4</td>
<td>26.1</td>
<td>(6)</td>
</tr>
<tr>
<td>S3B</td>
<td>-10.8</td>
<td>-10.8</td>
<td>(6)</td>
</tr>
<tr>
<td>S4A</td>
<td>22.9</td>
<td>29.4</td>
<td>(3)</td>
</tr>
<tr>
<td>S4B</td>
<td>18.4</td>
<td>7.5</td>
<td>(1)</td>
</tr>
<tr>
<td>S5A</td>
<td>8.0</td>
<td>1.0</td>
<td>(1)</td>
</tr>
<tr>
<td>S5B</td>
<td>32.2</td>
<td>20.5</td>
<td>(3)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>-0.6</strong></td>
<td><strong>-6.7</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Average weighted by sample size.

---

**Figure 2—Plot of error (%) versus diameter of historical trees alive at remeasurement. Error compares reconstructed diameter d.b.h. to that recorded in historical (1909–1913) data.**

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**Table 4—Error rate (percent) and sample size (in parentheses) for diameter (d.b.h. ≥10.16 cm) reconstruction of historical trees that had been cut subsequent to original plot establishment (1909–1913) and were stumps at time of remeasurement (1997–1999).**

<table>
<thead>
<tr>
<th>Subplot</th>
<th>1910*</th>
<th>1945</th>
<th>1980</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1A</td>
<td>40.6</td>
<td>28.4</td>
<td>(6)</td>
</tr>
<tr>
<td>S1B</td>
<td>22.1</td>
<td>10.2</td>
<td>(14)</td>
</tr>
<tr>
<td>S2A</td>
<td>57.5</td>
<td>43.1</td>
<td>(14)</td>
</tr>
<tr>
<td>S2B</td>
<td>42.0</td>
<td>29.1</td>
<td>(14)</td>
</tr>
<tr>
<td>S3A</td>
<td>61.1</td>
<td>45.9</td>
<td>(19)</td>
</tr>
<tr>
<td>S3B</td>
<td>33.3</td>
<td>19.1</td>
<td>(21)</td>
</tr>
<tr>
<td>S4A</td>
<td>54.4</td>
<td>38.2</td>
<td>(36)</td>
</tr>
<tr>
<td>S4B</td>
<td>43.8</td>
<td>26.8</td>
<td>(33)</td>
</tr>
<tr>
<td>S5A</td>
<td>7.5</td>
<td>-0.2</td>
<td>(4)</td>
</tr>
<tr>
<td>S5B</td>
<td>24.7</td>
<td>14.3</td>
<td>(10)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>43.7</td>
<td>28.7</td>
<td></td>
</tr>
</tbody>
</table>

*Earliest cut date tested for subplots S5A2 and S5B3 was 1914.

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establishment to be mapped, (3) trees that had died or been cut prior to plot establishment, and (4) large trees for which no increment core data existed. Tree density estimates were also affected by variations in decay functions used in the model. Varying the rate at which dead and downed material moved through decay class by 25 percent altered estimated tree densities by approximately 7 percent.

To more clearly evaluate reconstructed tree densities (1945 cut date and 50th percentile) we subtracted large cut trees that were not historically recorded, as well as trees for which no increment core center dates existed, less than or equal to plot establishment date (1909-1913). These trees were likely large regeneration that were less than 10.16 cm d.b.h. in 1909-1913.

<table>
<thead>
<tr>
<th>Subplot</th>
<th>Estbl</th>
<th>Total</th>
<th>Adjst1</th>
<th>Adjst2</th>
<th>Error (No. Trees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Adjst1</td>
<td>Adjst2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Number adjusted by removing cut trees that were not originally tagged. These trees were likely cut prior to plot establishment or large regeneration thinned such as on S3A and S3B.

Conclusions

Evaluation of reconstruction techniques revealed several key sources of error. These included field identification of historical trees, size reconstruction of live trees, and determination of tree death dates. Forest structures on the subplots were readily identified in the field after ± 90 years. Misses resulted in an underestimate of stand density by 5.7 percent or about three trees per hectare. Factors not addressed in this analysis but that may affect success rate of identification include disturbance such as fire, time, and experience level of personnel. Very little disturbance, outside of individual tree selection harvest, occurred on the subplots in this study. Intense fire had not occurred on any of the subplots since establishment and precommercial thinning had occurred only in S3A and S3B. No clear pattern related to initial or present density of forest structures emerged to affect identification success. Identification of preestablishment-aged structural evidence is important for implementing ecological restoration prescriptions in northern Arizona ponderosa pine forests (Covington and others 1997).

The reconstruction model tested in this analysis tended to overestimate tree diameters for live trees (11.9 percent), slightly underestimate (± 0.5 percent) dead and downed trees, and overestimate trees that had been cut (11.4 percent). For live trees, slightly greater inaccuracies were produced for smaller size classes. Possible explanations for live-tree errors include model equations used to predict bark thickness and d.b.h. from d.s.h. (Myers 1963; Hann 1976), unusable increment cores, particularly for trees that were especially fast- or slow-growing, and eccentricity of tree bases.

Although prediction of tree death date is difficult due to factors affecting snag longevity and condition, the d.b.h. estimates provided by the reconstruction model were relatively accurate. Accuracy here was likely affected by the interaction of death date estimates and reverse growth functions.

In our analysis, global cut dates were set in the model, although in reality, trees on the subplots were not all cut in the same year. This undoubtedly affected d.b.h. reconstruction errors. Cut dates for harvested “cohorts” could be individually coded in the model using additional information not examined in this study such as harvest records and stump decay classes.

Overestimation of d.b.h. coupled with death date and cut date uncertainties lead to overestimates of past tree density. However, our reconstruction techniques allowed reductions of these estimates based on increment core data and sizes of cut trees. Refinement of decay functions may allow better accuracy in stand density reconstruction.

The reconstruction techniques evaluated in this study appear to be robust and useful for estimating past forest structural characteristics. Although the model was used generally, adjustments could be made for specific sites using relationships developed from site-specific field data. The reconstruction techniques allow a better understanding of reference conditions in ponderosa pine forests of the Southwest. Further analysis will be done to reconstruct preestablishment structural conditions on these plots.

Acknowledgments

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