Ponderosa Pine Forest Reconstruction: Comparisons With Historical Data

David W. Huffman
Margaret M. Moore
W. Wallace Covington
Joseph E. Crouse
Peter Z. Fulé

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; Fulé 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stands, maintained by frequent surface fires prior to Euro-American settlement (about 1876) of the region, have been replaced by closed canopied forests with resulting deleterious effects on biological diversity and ecological function (Covington and Moore 1994a).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 living trees, direct measurement of remnant woody evidence, and backwards radial growth modeling (Fulé 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 presettlement 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.,

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David W. Huffman is Research Specialist, Margaret M. Moore is Professor of Plant Ecology, W. Wallace Covington is Regents' Professor of Forest Ecology, Peter Z. Fulé is Research Professor of Forest Ecology, and Joseph E. Crouse is Research Technician, Ecological Restoration Institute, School of Forestry, Northern Arizona University, Flagstaff, AZ 86011.

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., *Blepharoneuron tricholepis* (Torr.) Nash, and *Sitanion hystrix* (Nutt.) J.G. Smith, and forbs, *Achillea millefolium* var. *occidentalis* D.C., *Pseudocymopterus montanus* (Gray) Coult. & 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 m^2 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 (presettlement, "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: presettlement, 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 1985) and classified as presettlement in age. We classified trees as "preplot-aged" (in other words, established prior to historical plot measurement) if they did not meet presettlement 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 cored 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 presettlement (37.5 cm at d.b.h.) and classification was made based on bark characteristics. Trees with black bark and smaller than the minimum presettlement and preplot diameters were classified as postplot.

Diameter at stump height and crown radius (average of two measurements) was measured for all presettlement 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

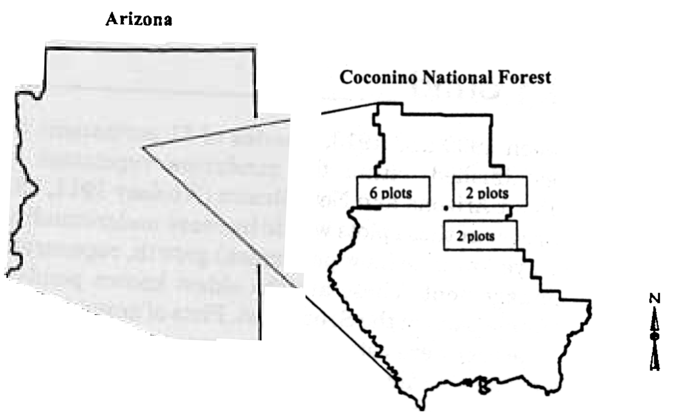

Figure 1—Study area showing general location of historical plots. Shown are the number of subplots remeasured in each location. Coconino National Forest boundary is outlined and Flagstaff, AZ, is shown as the point in the center.

crown radius was measured for a 20 percent random subsample of live postplot (all species) trees. Increment cores were stored in paper straws until denrochronological analysis could be done in the laboratory. Dendrochronological analysis involved cross-dating cores (Stokes and Smiley 1996) 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 (1876; Fulé and others 1997) were also measured. Our age classification 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 measured 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 average 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 empirical 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 diameter output from the reconstruction model with data available from the historical ledgers. Because data in historical ledgers was restricted to trees greater than or equal to 10.16 cm d.b.h., we limited our analysis of stand density to trees of this size. To test reconstruction sensitivity, we varied cut date and decay rate parameters in the model. Cut dates of 1910 (1914 for the two plots established in 1913), 1945, and 1980 were tested for field-measured stumps, and dead/down trees were moved backward through decay classes at rates corresponding to the 25th, 50th, and 75th percentiles found in other studies (Roger and others 1984). Thus, five model iterations were done for each subplot reconstructed to historical establishment dates. 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 remnant structures 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 stand 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 overestimated 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 fast- or slow-growing trees for which increment data were unavailable (rotten tree centers, incomplete cores, and so forth).

Table 1—Number of live trees on Woolsey subplots in Arizona at establishment (1909–1913) and the number missed during remeasurement (1997–1999).

Subplot	No. trees on subplot[a]	No. trees missed	Error
			percent
S1A	26	1	3.8
S1B	25	2	8.0
S2A	82	5	6.1
S2B	72	2	2.8
S3A	47	9	19.1
S3B	58	2	3.4
S4A	87	8	9.2
S4B	61	0	0.0
S5A	20	1	5.0
S5B	83	2	1.2
Average[b]			5.7

[a]Number of historical trees on subplot recorded on 1915 maps.
[b]Overall average = (S No. trees missed/S No. Trees on subplot) * 100.

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

Plot	Error	
S1A		17
S1B		9
S2A		29
S2B		44
S3A		8
S3B		29
S4A		37
S4B		23
S5A		14
S5B		67
Average[a]		

[a]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).

	Decay percentile		
Subplot	25th	50th	75th
		40.0 (2)	26.8 (2)
		–2.1 (2)	–10.2 (2)
		–25.2 (25)	–26.3 (28)
		31.6 (6)	11.1 (6)
		40.4 (6)	26.1 (6)
		–10.8 (5)	–10.8 (6)
		22.9 (1)	29.4 (3)
		18.4 (1)	7.5 (1)
		8.0 (1)	1.0 (1)
		32.2 (3)	20.5 (3)
		–0.6	–6.7

[a]Average weighted by sample size.

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

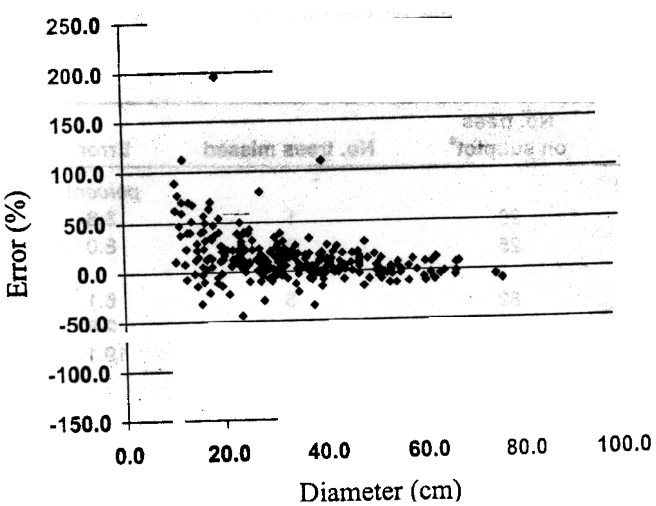

Figure 2—Plot of error (%) versus diameter of historical trees alive at remeasurement. Error compares reconstructed diameter d.b.h. to that recorded in historical (1909–1913) data.

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).

	Cut date		
Subplot	1910[a]	1945	1980
	40.6 (6)	28.4 (6)	(6)
	22.1 (14)	10.2 (14)	(14)
	57.5 (14)	43.1 (14)	(14)
	42.0 (14)	29.1 (14)	(14)
	61.1 (18)	45.9 (18)	(18)
	33.3 (21)	19.1 (21)	(21)
	54.4 (36)	36.2 (36)	(36)
	43.8 (33)	26.8 (33)	(33)
	7.5 (4)	–0.02 (4)	(4)
	24.7 (10)	14.3 (10)	(10)
	43.7	28.7	

[a]Earliest cut date tested for subplots S5A2 and S5B3 was 1914; these plots were historically established in 1913.
[b]Average weighted by sample size.

Table 5—Numbers of trees (≥10.16 cm d.b.h.) for subplots reconstructed to plot establishment date (1909–1913). Comparison shows number of historically measured trees (Estbl), total number of trees reconstructed (Total), and the number of trees after reconstruction totals were adjusted (Adjst1 and Adjst2). Error (No. trees is equal to (Adjst2 - Estbl).

Subplot	Estbl	Total	Adjst1[a]	Adjst2[b]	Error (No. Trees)
					18
					19
					51
					47
					27
					22
					10
					10
					17
					36

[a]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.

[b]Number adjusted by removing trees not in original ledger data but having increment core center dates of 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.

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 decay percentile) we subtracted large cut trees that were not historically recorded, as well as trees for which increment core center dates were less than plot establishment dates. We presumed these to represent trees cut prior to plot establishment and trees too small to be historically measured, respectively. Subtraction resulted in tree density overestimates of 10–51 trees per subplot (table 5). Trees reconstructed in excess of historical densities were mainly dead and down trees for which death dates were inaccurately estimated.

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. Missed trees 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 presettlement-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 (–0.6 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 presettlement structural conditions on these plots.

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