ELSEVIER

Forest Ecology and Management 155 (2002) 271–278

Forest Ecology and Management

www.elsevier.com/locate/foreco

Evaluating ponderosa pine regeneration rates following ecological restoration treatments in northern Arizona, USA

John Duff Bailey*, William Wallace Covington

School of Forestry, Northern Arizona University, P.O. Box 15018, Flagstaff, AZ 86011-5018, USA

Abstract

Ecosystem restoration is emerging as a dominant ponderosa pine (*Pinus ponderosa* var. *scopulorum*) forest management objective in the semi-arid southwestern USA. Restoration consists predominantly of mechanical thinning in overly dense stands and reintroduction of ground fire, and therefore can meet a variety of community and agency objectives associated with forest ecosystem health, wood production, fire protection, recreation and scenic beauty. Ecosystem restoration and long-term multi-aged stand management creates the growing space, microclimate and seedbed conditions necessary for natural regeneration via density reduction and regular understory burning. Several long-term research studies have demonstrated regeneration >100 seedlings/ha within a few years of overstory treatment when a relatively dense overstory canopy is left as a seed source; based on the literature, the reduced density of overstory seed-producing trees following restoration treatment still supplies sufficient viable seed over time for regeneration. Our remeasurement data of treated sites showed only 18–41 seedlings/ha in the absence of fire due perhaps to the reduced density of seed-producing overstory trees or lack of adequate (fire prepared) seedbed. Repeated prescribed burning of surface fuels can enhance the seedbed, but limits seedling survival typically during the first two decades. Survivors develop into fire resistant saplings at 10 cm stump diameter and 3 m height. Seedling density in a restoration study plots that has received two burning treatments, in 1992 and 1998, was only 12 seedlings/ha. Seedling density in the 30 growing stock level treatments at Taylor Woods averaged only 7 seedlings/ha following one burning cycle. However, even this relatively low natural regeneration rate is sufficient to supply the 3.6 trees/ha/decade needed to sustain tree densities like those present before Euro-American settlement. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Ponderosa pine; Ecological restoration; Regeneration; Multi-aged management

1. Introduction

Ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelm.) ecosystems in the southwestern USA are semi-arid forests with ~50 cm of precipitation/year. Regeneration under native, presettlement (prior to Euro-American settlement) conditions prior to around 1876 was limited by drought, competition with grassland vegetation, frost heaving, and browse by rodents and ungulates (Pearson, 1950; Schubert, 1974; White, 1985; Harrington, 1987; Covington and Moore, 1994). Open spaces among trees were maintained by regular surface fires ignited by lightning and/or indigenous peoples on a 3–7 year interval, which prepared localized small seedbeds for pine with reduced grass competition; however, such periodic fire also regulated seedling survival. Crown fires in southwestern ponderosa pine ecosystems before Euro-American settlement are

---

* Corresponding author. Tel.: +1-520-523-6582; fax: +1-520-523-1080.
E-mail address: john.bailey@nau.edu (J.D. Bailey).

PII: S0378-1127(01)00564-3

thought to have been rare (Cooper, 1960; Covington and Moore, 1994), and the species is therefore poorly adapted to stand-replacing events (e.g. cones are not serotinous). Given periodicity of seed years and regular surface fires, regeneration rates averaged only 3.6 trees/ha/decade, but presumably were sufficient to maintain the structure of these stands, with densities estimated at <100 trees/ha (Mast et al., 1999). That study identified four decades between 1600 and 1800 that had no representatives in the dendrochronological record.

Beginning in 1876, large-tree logging, livestock grazing and disruption of the natural frequent-fire regime resulted in the long-term survival of a pulse of regeneration previously unseen in the southwest (Covington and Moore, 1994). After only three decades, Lang and Stewart (1910) documented 268 new trees/ha, a 337% increase in stand density. Some areas on the Coconino Plateau now have >2000 trees/ha (Covington and Moore, 1994). These stand conditions present major ecosystem health and wildfire control issues for the region, and the fire seasons of 1996 and 2000 bear witness to abnormal density and related fuel accumulations in these forests. As land managers move to restore many of these areas to presettlement conditions (or something that is sustainable and that approximates those conditions), forest scientists need to look again at issues of pine regeneration and growth rates. Will currently observed regeneration rates suffice for sustainability?

Tree regeneration rates are regulated by the presence of sufficient seed-producing adults, periodicity of their cone/seed crops, predation on cones/seeds, seed viability rates, seedbed conditions and germinant survival, and early seedling growth relative to microclimate, fire and competitive stresses. Periodicity of ponderosa pine cone/seed crops and predation on cones/seeds are major limitations of regeneration in the Southwest (Pearson, 1950; Schubert, 1974; Rietveld, 1978). Mature trees produce $\geq$1 kg of seed only every 3 years on average (Schubert, 1974); as much as 100% of the seed is non-viable and/or preyed upon during intervening years (Blake et al., 1985). Once on the ground, most seed is consumed by rodents in intervening years (Heidmann et al., 1982). In general, sufficient seed is therefore available for new regeneration only once or perhaps twice/decade.

The periodicity of spring and summer drought combined with vegetation competition and allelopathy cause severe seedling mortality once seeds germinate (Pearson, 1950). Rietveld (1975) determined that grass communities must be disturbed through mechanical means or fire over at least 50% of the ground surface to ensure adequate even-aged management stocking—but restoration and/or low-density multi-aged management would require much less regeneration. Grass, forb and sedge production respond strongly to levels of canopy closure (Moore and Dieter, 1992) producing a trade-off between resources for new germinants and competition. In addition, Rietveld (1975) and Harrington (1987) suggest reductions in ponderosa pine germination rates and radicle development associated with phytotoxic grasses and Gambel oak (*Quercus gambelii*), respectively. Cormier (1990) found that natural regeneration of ponderosa pine on limestone soils following shelterwood harvesting could be best predicted from time since harvest (positive coefficient, up to 16 years), residual basal area following harvest (negative), and site index (positive). These represent the time necessary to have sufficient seed production with early germination conditions, availability of growing space following disturbance and inherent site quality, respectively.

The role of fire in long-term pine regeneration rates is also important. In low-intensity prescribed fire treatments in northern Arizona, Harrington and Sackett (1990) found partial to full consumption of litter over 75% of the ground surface; mortality of seedlings <0.3 m in height was high in these areas. Gaines et al. (1958) recorded 98% mortality in ponderosa pine seedlings (<0.3 m height) and 70% mortality in saplings (>0.3 m in height to <2.5 cm dbh) following prescribed fire treatment. Surviving seedlings and saplings came predominantly from the 25% unburned ground surface, and from saplings >1.2 m in height, which have survival rates >50% (Gaines et al., 1958).

Given requirements for ponderosa pine germination and regeneration growing space (Schubert, 1974) and current forest conditions in much of northern Arizona, decades could pass (and have passed) without vigorous regeneration. For a silviculturist, the shortage of young vigorous trees in these forests is as troublesome as the lack of large presettlement trees.

The objective of this paper is to review this conceptual framework for ponderosa pine regeneration and to evaluate whether pine regeneration following ecological restoration treatments in southwestern ponderosa pine forests will be sufficient to sustain the ecosystem. We examine data from local long-term research installations together with recent remeasurements, both with and without prescribed surface fire treatments, and compare them with the known age structure of presettlement forests.

2. Methods

Seedling data were collected from two neighboring long-term research installations in northern Arizona: the Taylor Woods level of growing stock (LOGS) and Gus Pearson natural area (GPNA) ecological restoration study sites. Both sites are located 15 km northwest of Flagstaff, AZ (at 35°16′11″N, 111°44′30″W) on the Coconino National Forest, and are pure ponderosa pine overstories. Soils are basalt- and volcanic cinder-based forming a fine montmorillonitic complex of frigid Typic Argiborolls and Argiboralfs with an average site index of 25 m in 100 years (Minor, 1964). Slopes are gentle (<5%) with southern and western aspects. This specific area receives an average of 57 cm of precipitation annually, with about half in the form of winter/spring snowfall and half in late summer rains following an extensive dry period from May to July. Elevation is 2240 m with 94 frost-free growing days. The understory is dominated by native grasses (mostly Arizona fescue, *Festuca arizonica* and mountain muhly, *Muhlenbergia montana*) and a variety of herbaceous species; *Ceanothus fendleri* is the only common shrub.

Taylor Woods LOGS study site was established in 1962 and, for every 10 years since, replicate 0.5 ha plots within the study area have been maintained at a range of growing stock levels (GSLs) within an even-aged management strategy (Ronco et al., 1985). We examined the plots that have 30 and 60 GSL treatments, which are characterized as heavy regular thinnings corresponding to 6.9 and 13.8 m^2/ha of basal area at 25 cm quadratic mean diameter. Both thinnings produced modest pine regeneration and grass responses beginning with the first harvesting activity in 1962. Overstory tree information has been measured periodically using standard mensurational techniques (Ronco et al., 1985). We visually estimated percent cover of grass and herbaceous plants in September 1997 and again in 1998 with eight randomly located subplots per treatment area using 1 m^2 sampling frames. A prescribed fire treatment was introduced into this study area in October 1998 when half of each replicate plot was burned with a light surface fire (maximum flame length <1 m).

The GPNA is a 3 ha research site established in 1992 to test a range of ecosystem responses to two ecological restoration treatments in a ponderosa pine ecosystem (Covington et al., 1997). ‘Partial restoration’ was a mechanical thinning of the overabundance of smaller diameter trees (<50 cm dbh) that developed from a 1919 regeneration event. ‘Full restoration’ was an identical thinning that included mechanical replacement of pine surface fuels with grass and herbaceous fuels followed by a light prescribed surface burn. The complete restoration treatment area was burned a second time in the fall of 1998; both burns had maximum flame length <1 m. Fig. 1 presents the stand diameter distribution following mechanical overstory thinning in the GPNA, combining the partial and full restoration areas. The restoration left 12.6 m^2/ha of basal area, 25% of which is in the 75–105 cm diameter classes. This presettlement restoration prescription serves as one model for ponderosa pine restoration in the southwest and is a likely target for treating much of the forested area in the Flagstaff wildland-urban interface. Over- and understory measurements have been taken periodically since the original treatment in 1992.

Current overstory densities at the GPNA restoration site are similar to (and bracketed by) those at the Taylor Woods study site (Table 1). These overstory densities yield similar understory grass and herbaceous plant responses despite the differences between the objectives of the management: restoration of multi-aged stand structure versus maintenance of even-aged structure. Such understory plant responses to overstory density and thinning have been previously demonstrated in the Southwest (e.g. Moore and Dieter, 1992).

We conducted a 100% survey of the area for ponderosa pine seedlings at least 20 cm in height in both study areas in 1999, both in the burned and unburned subplots at Taylor Woods and in the partial

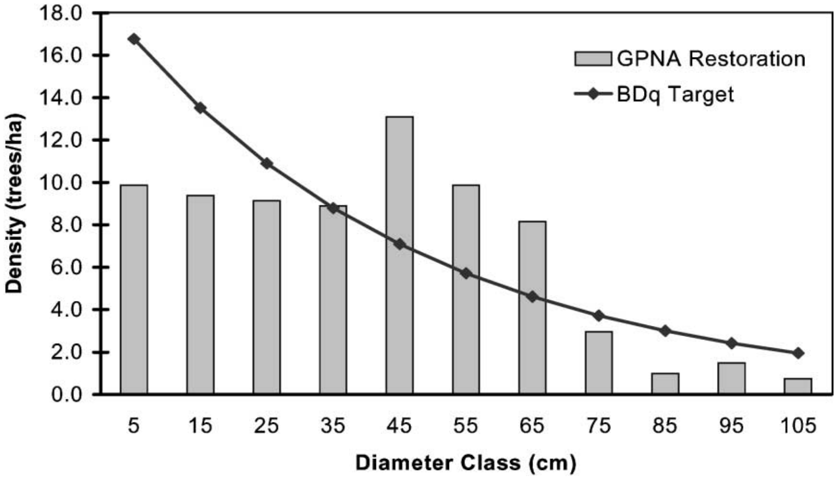

Fig. 1. Ponderosa pine diameter class distribution (bars) following presettlement restoration treatment at the GPNA in northern Arizona, with an overlaid line showing a proposed multi-aged BD*q* distribution (12.4–105–1.24) to approximate presettlement basal area, density and maximum diameter.

and full restoration treatments at the GPNA. Pine seedlings were tallied by species, 15 cm height class, and one of three condition codes based primarily on damage severity from fire (in burned subplots): living, declining—partial scorch, and recent death—full scorch. Diameters were also recorded for tallied seedlings at Taylor Woods. Charred and scorched remnants of seedlings, most with needles still attached, served as evidence of pre-burning seedlings. Overall density and damage rates were summarized for each area and expanded to a per area basis.

Other data presented in this paper are manipulations of others' published data. We summarized data presented in much greater detail in Sackett (1984). Also, presettlement tree density and diameter distribution from Covington et al. (1997) and Mast et al. (1999) were fit into an uneven-aged (multi-aged) silvicultural framework based on BD*q*: basal area, maximum diameter, and *q*-ratio (Smith et al., 1997). Specification of BD*q* for a stand is an attempt to balance standing tree density with expectations for growth and mortality up to some maximum diameter. Such an uneven-aged silvicultural approach is a logical fit given the conceptual intent of ecological restoration (e.g. sustainable forest cover) and resulting overstory diameter distribution.

Finally, for purposes of evaluating regeneration requirements, we assumed minimum estimates of

Table 1
Observed overstory basal area and stand density, grass and herbaceous plant cover, and ponderosa pine regeneration rates at two study sites in northern Arizona: Taylor Woods LOGS and GPNA restoration site[a]

Study site	Treatment	Overstory		Understory	
		Basal area (m^2/ha)	Density (trees/ha)	Grass and herb cover (%)	Pine regeneration (seedlings/ha)
Taylor woods	30 GSL	11.4	65	25	41
	60 GSL	19.9	188	16	18
GPNA	Complete[b]	12.4	71	24[c]	14
Restoration	Partial	12.8	79	19[c]	60

[a] GSL is a measure of density minus stand basal area when quadratic mean diameter is 25 cm.

[b] Complete restoration included a prescribed fire (Covington et al., 1997).

[c] Daubenmire cover.

positive factors affecting regeneration rates (e.g. seed production) and maximum estimates of negative factors (e.g. fire mortality). Thus, conservative but realistic assessments of potential regeneration issues are identified, which can be addressed with future research as necessary.

3. Results and discussion

3.1. Regeneration requirements

A BD*q* of 12.4–105–1.24 (55–42–1.24) was assigned as the best approximation to presettlement conditions and stand diameter distribution following ecological restoration treatments (Fig. 1). Many areas in northern Arizona have an even lower density of trees in the 45–65 cm diameter classes given past harvesting practices. Such stands fit this BD*q* more closely up to 65 cm, but lack even more trees >70 cm. Given spatial variability in density of the largest ponderosa pine trees within the landscape, this BD*q* can alternatively be viewed as 9.5–75–1.24 with up to 25% of stand basal area carried above the 70 cm diameter limit without any restraint on actual diameter class distribution or maximum tree size. At the lower end of the distribution (Fig. 1), multiple regeneration events over several decades are necessary to supply <25 cm diameter trees required by this BD*q*; however, that regeneration is more likely now than prior to restoration given the availability of new growing space on the site.

The restoration distribution and BD*q* ($q = 1.24$) shown in Fig. 1 is consistent with observed mortality rates of ponderosa pine >30 cm dbh (Pearson, 1950; Mast et al., 1999), and this diameter is the first requirement for assessing regeneration requirements. Given 8.8 trees/ha 35 cm in diameter and a radial growth rate of 1.6 cm/decade (US Department of Agriculture Forest Service, unpublished data from the Taylor Woods site), these trees require about 30 years to grow into the 45 cm diameter class. Pearson (1950) observed a mortality rate of 10% for these diameter classes well below the 20% mortality implied by a *q*-ratio of 1.24. Observed mortality rates increased for larger trees (Pearson, 1950). Radial growth rates slowed with increasing diameter such that the 55 and 65 cm diameter classes match exactly. A *q*-ratio of 1.24 underestimates mortality for diameter classes >65 cm.

3.2. Regeneration densities

Observed regeneration densities in these two long-term study sites (Table 1) confirmed the importance of both reduced overstory density at Taylor Woods (due to shading and resource competition) and presence of fire (for seedbed preparation). The 30 GSL treatment at 65 trees/ha contained twice the number of seedlings as the higher density 60 GSL treatment (188 trees/ha). The low-density partial restoration treatment (79 trees/ha) had a comparable regeneration density to the 30 GSL treatment. These regeneration densities were low by many standards, particularly in other parts of the world with other management objectives; however, they are more than sufficient to supply either the BD*q*/restoration diameter distribution (Fig. 1) or the minimum requisite 3.6 trees/ha/decade determined by Mast et al. (1999).

Regeneration appeared successful despite a reduction in the number of seed producing trees following thinning, and their ability to produce and distribute viable seed. Heidmann et al. (1982) established a requirement for 12 seed-producing trees/ha >65 cm dbh to achieve full stocking—an even-aged management objective of 1000 seedlings/ha over 70% of a treatment area. Target regeneration for restoration or multi-aged management objectives is less than one-tenth of this even-aged management objective, suggesting a requirement of only one or two large seed-producing tree/ha which is provided by ecological restoration treatments. The location of these trees and ability to disperse seed obviously affects regeneration location, but not its frequency at a landscape scale.

3.3. Role of fire

Pre-burn seedling density in 1998 in the full restoration treatment was 96 seedlings/ha, twice that of the partial restoration. Sackett (1984) found a greater than three-fold increase in seedling density in burned areas relative to control areas, 6420 versus 2057 seedlings/ha, respectively, which he measured 1 year following burning in 1976. That year happened to be a good seed year within that decade. Eighty-three

Table 2
Summary table from data by Sackett (1984) showing regeneration densities and ratios between burned and control plots at Chimney Spring Interval Burning study site in northern Arizona

Treatment	Regeneration density (seedlings/ha)		
	Burned	Control	Burned:control ratio
1983 germination	222000	64000	3.5:1
1987 pre-burn	37000	3000	12.3:1
4-year survival rate (%)	17	5	
1987 post-burn	20000		6.7:1
Fire mortality rate (%)	46		

Table 3
Fire mortality of ponderosa pine seedlings in four 0.5 ha research plots with low overstory density in the Taylor woods LOGS and in the GPNA complete restoration study site (3 ha) following a prescribed fire in autumn 1998[a]

Study area	Treatment	Pre-burn density (seedlings/ha)	Post-burn density (seedlings/ha)	Fire mortality (%)
Taylor woods	30 GSL	7	5	29
		14	9	36
LOGS				
	Average	10	7	33
	60 GSL	1	1	0
		8	4	50
	Average	5	3	43
GPNA	Complete restoration	92	14	76

[a] One hundred percent survey of pine seedlings in all five treatment plots.

percent of the seedlings in the burned plots had germinated on mineral soil (Sackett, 1984). Two years later, densities had fallen to 1235 and 0 seedlings/ha, respectively, in burned and control areas. Table 2 summarizes regeneration data following another excellent seed year in 1983 (adapted from Sackett, 1984). Burning has been recognized as important for ponderosa pine regeneration as early as Pearson (1923).

Though burning enhances the seedbed for ponderosa pine, it also limits short-term survival of seedlings given crown scorch and cambium injury. Survival rates measured at Taylor Woods (Table 3), with a large range of seedling/sapling size, were similar to those published by Sackett (1984). All saplings >5 cm diameter at stump height and >2 m in total height were still alive following surface fire despite evidence of scorch at their bases. Harrington and Sackett (1990) and Gaines et al. (1958) similarly recorded little to no mortality of larger saplings (>10 cm dbh). Fire mortality was slightly higher (76%) at the GPNA complete restoration treatment where most (78%) of the seedlings were <60 cm in height, having germinated since 1992 (Table 3). The GPNA treatment area was extremely dense (3095 trees/ha) prior to treatment and had little advance reproduction from prior to 1992 to carry over into the restoration (Covington et al., 1997). Fire mortality was lower (only 5 of 14, 36%) in these seedlings >60 cm in height. There were no seedlings/saplings greater than 1 m in height to compare to saplings at Taylor Woods. The survival rates shown in Table 2, adapted from Sackett (1984), are based on seedlings/saplings of unknown size.

4. Conclusions and management implications

Ecological restoration and multi-aged management of southwestern ponderosa pine forests will not suffer from a shortage of pine regeneration. Our data, along with that in the literature, establishes that adequate regeneration will be available most decades for most areas following ecological restoration and/or multi-aged management treatments that include regular prescribed fire. Most decades (including the 1990s for our data) have provided one or two good seed years for a sufficient number of residual overstory trees, and there is no reason to expect this to change in the near future. These good seed years have compensated for and will continue to overwhelm natural levels of seed loss and predation. Mechanical thinning of the overstory and prescribed surface fire provide the necessary growing space for germination and early seedling growth in the order of thousands of seedlings/ha, given fire to assist with seedbed preparation and temporary disturbance of understory communities. The heavy thinning associated with ecological restoration and/or low-density multi-aged management provides a near-maximum amount of growing space for an extended time period. Low but still adequate densities of seedlings regenerate even without fire given sufficient overstory thinning.

A hypothetical scenario and some simple mathematics demonstrate that regeneration densities would not fall below that required for ecological restoration and/or low-density multi-aged management. Assume that a restoration treatment leaves 5 stems/ha of advanced regeneration and is followed by two good seed years/decade producing 1000 seedlings/ha and good growth rates for 40% of those seedlings (0.5 cm radial growth/year). Assume 90% survival of larger (>5 cm) seedlings and 25% survival of smaller seedlings through two prescribed surface fires/decade. With these assumptions, regeneration density stabilizes over the long term at 400 seedlings/ha, approximately 100 of which are 5–10 cm in diameter and well stationed to move into the overstory diameter distribution. These seedlings/saplings are more than sufficient to provide the 3.6 or 17 seedlings/ha required for presettlement restoration or multi-aged management, respectively. Seeding, germination and growth rates would have to be reduced substantially below those in the literature to approach even 17 seedlings/ha.

Periodic regeneration failures are likely, however, on some hectares during some decades. Mast et al. (1999) report four decades from 1600 to 1800 A.D. without representation in the dendrochronological record for this area. However, both ecological restoration and low-density multi-aged management systems can accommodate periodic failures during natural biotic and climatic cycles, even with modest anthropogenic change (e.g. global change and invasion by exotic plants). Only sustained conditions that are well outside the known historical range of natural variability for southwestern ponderosa pine ecosystems threaten the sustainability of natural regeneration. Indeed, the current overabundance of smaller diameter pine trees and related biomass/fuel accumulations are such a deviation from the range of natural variability in many of our southwestern forests. This condition is a far greater threat to sustainable ponderosa pine regeneration and forms the impetus for ecological restoration and multi-aged management.

Acknowledgements

Many thanks are due to the Ecological Restoration Institute at Northern Arizona University, and especially Pete Fulé for his contributions. Thanks also to Karen Goodwin for her review and continuing interest in this topic.

References

Blake, E.A., Wagner, M.R., Koerber, T.W., 1985. Insects destructive to ponderosa pine cone crops in northern Arizona. In: USDA For. Serv. Gen. Tech. Rep. INT-203. Intermountain For. Exp. Sta., Ogden, UT, pp. 238–242.

Cooper, C.F., 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. Ecol. Monogr. 30 (2), 129–164.

Cormier, K.L., 1990. Modeling natural regeneration of even-aged ponderosa pine following shelterwood cutting in northern Arizona. M.S. thesis, Northern Arizona University, Flagstaff, AZ, 69 pp.

Covington, W.W., Moore, M.M., 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. J. For. 92 (1), 39–47.

Covington, W.W., Fulé, P.Z., Moore, M.M., Hart, S.C., Kolb, T.E., Mast, J.N., Sackett, S.S., Wagner, M.R., 1997. Restoring ecosystem health in ponderosa pine forests in the southwest. J. For. 95 (4), 23–29.

Gaines, E.M., Kallander, H.R., Wagner, J.A., 1958. Controlled burning in southwestern ponderosa pine: results from the Blue Mountain Plots, Fort Apache Indian Reservation. J. For. 56, 323–327.

Harrington, M.G., 1987. Phytotoxic potential of Gambel oak on ponderosa pine seed germination and initial growth. USDA For. Serv. Res. Paper RM-277. Rocky Mtn. For. and Range Exp. Sta., Fort Collins, CO, 7 pp.

Harrington, M.G., Sackett, S.S., 1990. Using fire as a management tool in southwestern ponderosa pine. In: USDA For. Serv. Gen. Tech. Rep. RM-191. Rocky Mtn. For. and Range Exp. Sta., Fort Collins, CO, pp. 122–133.

Heidmann, L.J., Johnson, T.N., Cole, Q.W., Cullum, G., 1982. Establishing natural regeneration of ponderosa pine in central Arizona. J. For. 80, 77–79.

Lang, D.K., Stewart, S.S., 1910. Reconnaissance of the Kaibab National Forest. USDA For. Serv., Unpublished Report.

Mast, J.N., Fulé, P.Z., Moore, M.M., Covington, W.W., Waltz, A.E.M., 1999. Restoration of presettlement age structure of an Arizona ponderosa pine forest. Ecol. Appl. 9 (1), 228–239.

Minor, C.O., 1964. Site-index curves for young-growth ponderosa pine in northern Arizona. USDA For. Serv. Res. Note RM-37. Rocky Mtn. For. and Range Exp. Sta., Fort Collins, CO, 8 pp.

Moore, M.M., Dieter, D.A., 1992. Stand density index as a predictor of forage production in northern Arizona pine forests. J. Range Manage. 45, 267–271.

Pearson, G.A., 1923. Natural reproduction of western yellow pine in the southwest. USDA For. Serv. Bull. 1105, Washington, DC, 143 pp.

Pearson, G.A., 1950. Management of ponderosa pine in the southwest. USDA Agriculture Monograph No. 6, Washington, DC, 218 pp.

Rietveld, W.J., 1975. Phytotoxic grass residues reduce germination and initial growth of ponderosa pine. USDA For. Serv. Res. Paper RM-153. Rocky Mtn. For. and Range Exp. Sta., Fort Collins, CO, 15 pp.

Rietveld, W.J., 1978. Forecasting seed crops and determining cone ripeness in southwestern ponderosa pine. USDA For. Serv. Gen. Tech. Rep. RM-50. Rocky Mtn. For. and Range Exp. Sta., Fort Collins, CO, 12 pp.

Ronco Jr., F., Edminster, C.B., Trujillo, D.P., 1985. Growth of ponderosa pine thinned to different stocking levels in northern Arizona. USDA For. Serv. Res. Paper RM-262. Rocky Mtn. For. and Range Exp. Sta., Fort Collins, CO, 15 pp.

Sackett, S.S., 1984. Observations on natural regeneration in ponderosa pine following a prescribed fire in Arizona. USDA For. Serv. Res. Note RM-435. Rocky Mtn. For. and Range Exp. Sta., Fort Collins, CO, 8 pp.

Schubert, G.H., 1974. Silviculture of southwestern ponderosa pine: the status of our knowledge. USDA For. Serv. Res. Paper RM-123. Rocky Mtn. For. and Range Exp. Sta., Fort Collins, CO, 71 pp.

Smith, D.M., Larson, B.C., Kelty, M.J., Ashton, P.M.S., 1997. The Practice of Silviculture: Applied Forest Ecology. Wiley, New York, 537 pp.

White, A.S., 1985. Presettlement regeneration patterns in a southwestern ponderosa pine stand. Ecology 66, 589–594.