Natural Loblolly and Shortleaf Pine Productivity Through 53 Years of Management under Four Reproduction Cutting Methods

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ABSTRACT: *A study was initiated in 1943 to evaluate the long-term productivity of loblolly (*Pinus taeda *L.) and shortleaf pines (*P. echinata *Mill.) when managed under four reproduction cutting methods-clearcut, heavy seedtree, diameter-limit, and selection-on the Upper Coastal Plain of southeastern Arkansas. Early volume production reflected retention residual pines, and the clearcut was the least productive method through the first 36yr. After 53 yr, there were no statistically significant (P = 0.07) differences among cutting methods in sawlog volume production, which averaged 3,800 ft³/ac. In terms of sawlog volume (bd ft/ac, Doyle scale), total production on clearcut, seedtree, and selection plots exceeded (P < 0.01) that on diameter-limit plots by 37%, but there were no differences in sawlog volume production among the other cutting methods. Results suggest that forest landowners should consider the advantages and disadvantages of each cutting method when planning their long-term objectives. South. J. Appl. For. 25(1):7–16.*

Key Words: Clearcuts, diameter-limit cutting, *Pinus taeda, P. echinata,* seedtree cutting, selection management.

In the southeastern United States, southern yellow pines represent a significant timber resource, and most of the South's second (1900-1968) and third (1968-2000) forests originated from natural regeneration (Dougherty and Duryea 1991). Throughout this region, loblolly and shortleaf pines (*Pinus taeda* L. and *P. echinata* Mill., respectively) are common associates and are the most important and widespread of the southern pines (Baker and Langdon 1990, Lawson 1990). When mature forest stands are ready for harvest and subsequent regeneration, landowners must consider their objectives, economics, site conditions, rare and endangered species, concerns of adjacent property owners, competing vegetation, and which tree species are to be regenerated (Dougherty and Duryea 1991). One aspect of these numerous considerations is a measure of productivity from various reproduction cutting methods for these two important pines when they are to be regenerated naturally. In 1943, the USDA Forest Service initiated just such a study in the loblolly-shortleaf pine type. The cutting methods included merchantable clearcuts, heavy seedtree cuts, diameter-limit cuts, and selection cuts. The first two cutting methods resulted in even-aged stands while the latter two cutting methods produced uneven-aged stands.

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Originally, there were five objectives to the study: (1) would natural pine regeneration be adequate to sustain the cutting methods; (2) what volume of timber could be produced by each cutting method; (3) would hardwoods pose different problems under the various cutting methods; (4) what effect would the cutting methods have upon quality of the products that were produced; and (5) what were the costs and returns associated with each cutting method? Objectives 3, 4, and 5 were never addressed because of the introduction of herbicides to control competing hardwoods, changing standards for merchantability, modernizationofharvesting equipment, andinsufficient historical records on costs associated with the management of each cutting method through 53 yr.

Grano (1954) dealt with the first question when he reported that with proper hardwood control and an adequate seed source, good pine regeneration can be obtained with any of the four cutting methods that were tested. Baker and Murphy (1982) reported 36 yr of growth and yield from the four cutting methods. Using 11.6 in. dbh as the minimum size for sawlogs, they found that during those years, the selection, heavy seedtree, and diameter-limit cutting methods produced an average of about 12,800 bd ft/ac[1], while the merchantable clearcut method produced 9,400 bd ft/ac. Our objectives in this article are to present volume production through 53 yr of management under the four reproduction cutting methods and to discuss the advantages and disadvantages that might

[1] Throughout this article, board-foot volumes are reported in Doyle scale.

be encountered while using them to sustain productivity during a half-century of management.

Methods

Study Area

This study is located on the Crossett Experimental Forest in southeastern Arkansas. In the winter of 1942-1943, twelve 4.4 ac plots were established in previously unmanaged, second-growth, loblolly-shortleaf pine-hardwood stands that developed following diameter-limit cutting to a 14 in. stump diameter around 1915. At the time of establishment, the plots were typical of understocked second-growth stands in southeastern Arkansas, northern Louisiana, and eastern Texas. The study area is characteristic of productive sites for loblolly and shortleaf pines in the West Gulf region, which includes the Coastal Plain west of the Mississippi River and extends into East Texas and Oklahoma. Soils on the study area are principally Providence and Bude (Typic and Glossaquic Fragiudalfs, respectively) silt loams, but also include Arkabutla (Aeric Fluvaquent) silt loam along ephemeral drains. Site index for loblolly and shortleaf pines at age 50 yr ranges from 85 to 90 ft on Providence and Bude soils and 100 ft on Arkabutla soil (USDA 1979). All plots are contiguous and lay within an area of 53 ac.

Study Design and Reproduction Cutting Methods

Four reproduction cutting methods were imposed on the twelve 4.4 ac (440 ft by 440 ft) plots in a three-replicate, completely randomized design. Measurements were taken on the interior 2.5 ac (330 ft by 330 ft) of each plot. Before harvest, the study area averaged 147 merchantable-sized (>3.5 in. dbh) pines/ac, 61 ft^2/ac in basal area, 1,560 ft^3/ac in merchantable volume, and 4,000 bd ft/ac in sawlog volume. Initial harvesting was done between January and March 1943. The reproduction cutting methods were as follows:

Merchantable clearcut-In 1943, all merchantable-sized pines and hardwoods greater than 5.5 in. dbh were harvested. Based on historical records, regenerated pines on these plots were marked and commercially thinned for the first time in 1980-1981. Thinning was done from below to a residual basal area of 80 ft^2/ac. Using the same criteria, subsequent thinnings were conducted in November 1985 and December 1990.

Heavy seedtree cut-In 1943, all merchantable-sized pines and hardwoods were harvested with the exception of 15 to 20 dominant and codominant pines/ac (dbh > 11.5 in.) that were retained as seedtrees. Although seedtrees were intended to be greater than 11.5 in. dbh, about half were 9 to 11 in. dbh. A conventional seedtree cut would leave 6 to 10 trees/ac. Seedtrees were harvested in 1958, 15 yr after the initial cut. The first commercial thinning was in 1957, when 47% of pulpwood-sized (4 to 9 in. dbh) pines were removed. In 1980-1981, pines were marked and thinned from below to a residual basal area of 80 ft^2/ac. Using the same criteria, subsequent thinnings were conducted in November 1985 and December 1990.

Diameter-limit cut-In 1943, all pines greater than 11.5 in. dbh and all merchantable-sized hardwoods were harvested. Subsequent harvesting of pines and hardwoods greater than 11.5 in. dbh occurred in 1953, 1957, 1968, 1980-1981, and 1990.

Selection cut-Beginning in 1943, merchantable pines were harvested as single trees on a 5 yr cutting cycle. All merchantable-sized hardwoods were also harvested in 1943. Regulation of pine harvesting was by volume control (Baker et al. 1996). On these sites, a fully stocked uneven-aged stand of loblolly and shortleaf pines should contain 1,500 ft^3/ac or 7,500 bd ft/ac in sawlog volume. If stands were understocked, only 60 to 70% of periodic sawlog growth was removed during each cutting cycle until the stand reached full stocking. At full stocking, all sawlog growth during the cutting cycle was harvested at the end of the cutting cycle by removing the poorest quality trees and leaving the best across all dbh classes. In addition, pulpwood-sized (3.6 to 9.5 in. dbh) pines were thinned to permit the establishment and development of seedlings so as to maintain an uneven-aged structure. After 1943, additional harvests were conducted in 1948, 1953, 1957, 1963, 1968, 1980-81, 1985, and 1990.

Competition Control

Certain competition control measures were applied on all plots: (1) in 1946 and 1948, residual hardwoods greater than 3.5 in. dbh were felled to release pine regeneration; (2) in the spring of 1958, competing hardwoods were basally injected with the herbicide 2,4,5-T in diesel oil on all cutting method plots except the clearcuts; (3) in 1966, all plots except clearcuts were treated with 2,4,5-T applied from a tractor-mounted mist blower at the rate of 2 lb ae/ac; (4) in March 1980, the entire study area was prescribe burned to control small hardwoods and improve accessibility; (5) after the 1981 harvest, residual hardwoods greater than 1 in. dbh were controlled on all plots using basally injected Tordon® 101R[2] (picloram at 0.27 lb ae/gal and 2,4-D at 1.0 lb ae/gal).

Other competition control measures were applied only to specific reproduction cutting methods either to meet the need for establishment of natural pine regeneration on uneven-aged plots (diameter-limit and selection cutting methods) or simply to control nonpine competition on even-aged plots (clearcut and heavy seedtree cutting methods) as follows:

Merchantable clearcut-In spring 1943, plots were prescribe-burned to reduce logging slash and control small hardwoods. After 198 1, competition was controlled using prescribed winter bums on all three replications in November-December 1989 and on one replication in December 1995.

[2] The use of firm or trade names is for reader information and does not imply endorsement of any product or service by the U.S. Department of Agriculture. Discussion of herbicides in this article is not a recommendation of their use and does not imply that uses discussed here are registered by appropriate state or federal agencies.

Heavy seedtree cut-After 1981, competition was controlled using prescribed winter burns on all three replications in November-December 1989 and on two replications in December 1995.

Diameter-limit cut-After 1981, competition control was accomplished with herbicides: in 1984-1985 (Roundup@-glyphosate applied as a foliar spray from a rubber-tired tractor at 2 lb ai/ac in 100 gal of water/ac; or Velpar® L-hexazinone at 3 lb ai/ac applied with hand-held spotguns to the soil on a 3 by 3 ft grid), and in 1990 (Arsenal@ AC-imazapyr applied as a foliar spray from an articulated rubber-tired skidder at 0.5 lb ai/ac in 30 gal of water/ac).

Selection cut-After 1981, competition control was accomplished with herbicides: in 1986 (Velpar® L-hexazinone at 3 lb ai/ac applied with hand-held spotguns to the soil on a 3 by 3 ft grid), and in 1990 (Arsenal@ AC-imazapyr applied as a foliar spray from an articulated rubber-tired skidder at 0.5 lb ai/ac in 30 gal of water/ac).

Measurements and Data Analysis

Before each harvest, all merchantable-sized pines (dbh >3.5 in.) on the interior 2.5 ac plots were recorded by 1 in. classes. Stands were then marked to the cutting guidelines for each specific treatment, recording the dbh of marked trees by 1 in. classes. Volumes for the before-harvest stand and the harvested trees were calculated using local volume equations (Farrar et al. 1984). Merchantable volumes were calculated for trees greater than 3.5 in. dbh, and sawlog volumes were calculated for trees greater than 9.5 in. dbh. Stand values after harvesting were assumed to be the difference between the before-harvest stand and the harvested trees. Periodic annual increment was calculated as the difference in the before-harvest stand and the after-harvest stand from the most recent harvest divided by the number of years in the growth interval. Total volume production was calculated as the before-harvest volume plus the volume of trees harvested periodically minus the volume after the initial harvest in 1943. Localized wind damage on three plots caused the loss of merchantable pines which were not recorded before being salvaged. Consequently, those three plots were dropped from calculation of periodic annual increment (PAI) as follows: one selection plot during the 36-43 yr growth interval; one heavy seedtree and one selection plot during the 48-53 yr growth interval. To recover information on total volume production, growth for these intervals was assumed to be the mean of the undamaged plots of respective treatments.

In 1999, twenty-five 0.001 ac and 0.01 ac circular subplots were systematically established on each 2.5 ac interior plot to inventory pines, woody shrubs, and hardwoods in the seedling and sapling size classes. Seedlings ranged from more than 0.5 ft tall to 0.5 in. dbh, and saplings ranged from 0.6 to 3.5 in. dbh. Hardwoods and shrubs in the seedling size class were counted by rootstocks. A rootstock was comprised of either single or multiple stems (clump) which obviously arose from the same root system. The 0.01 ac subplots were also used to count merchantable-sized hardwoods by 1 in. dbh classes. Merchantable hardwood volumes after 55 yr were calculated using a local volume table (Reynolds 1959).

Analysis of variance was used to compare measured variables derived from the reproduction cutting methods. Stocking percents were analyzed following arcsine transformation, but only nontransformed data are presented. Differences between reproduction cutting method means were isolated by the Ryan-Einot-Gabriel-Welsch Multiple Range Test (a = 0.05) (SAS Institute 1989).

Results

Merchantable Clearcut

After the 1943 harvest, clearcut plots still averaged 13 trees/ac (Figure 1) in pines 3.6 to 5.5 in. dbh and basal area averaged 1 ft^2/ac. By 1957, researchers believed that the cutting method had already demonstrated that 4.4 ac areas could be regenerated naturally with pines if surrounded by stands with trees of seed-bearing size (Grano 1954). In a 1958 office report,[3] the principal investigator wrote that plots had developed into two-storied stands because some submerchantable pines were left 14 yr earlier, and a decision was made to discontinue measurements following the 1957 inventory. Consequently, data on these plots were not available from 1958 to 1979, when measurements resumed (Table 1).

Because of lack of thinning between 10 and 15 yr after study initiation, periodic annual increment (PAI) in basal area and merchantable volume on clearcut plots exceeded ($P < 0.01$) that on all other cutting methods by 121% and 84%, respectively (Table 1). Naturally, sawlog volume production on these clearcuts trailed the other treatments in early years, but PA1 for sawlog volume (both ft^3/ac and bd ft/ac) on the clearcuts exceeded ($P \leq 0.02$) both the diameter limit and selection methods during the growth interval of 36-43 yr and exceeded the diameter limit between 48-53 yr (Table 1). There was no difference in sawlog volume PA1 between the clearcut and heavy seedtree methods during the last three growth intervals.

Both merchantable volume and sawlog volume exhibited a rapid increase between 10 and 36 yr after the initial harvest, and total merchantable volume peaked in 1979 (Figure 2). The diameter distribution from 1979 through 1996 was bell-shaped and typical of even-aged stands (Figure 1). During three subsequent thinnings that occurred after 36 yr, sawlog volume continued to increase and averaged 584 bd ft/ac/yr between yr 48 and 53 (Table 1).

After 36 yr of management, merchantable volume production on clearcut plots averaged 11% higher (P c 0.01) compared to selection plots (Table 2). After 53 yr, that difference had increased ($P < 0.01$) to 29%. Over the course of 53 yr, total sawlog production on clearcut plots averaged more than 20,000 bd ft/ac which exceeded ($P <$ 0.01) the diameter-limit plots by 32% but was no different ($P > 0.05$) than heavy seedtree or selection cutting methods (Table 2).

[3] Grano, C.X. 1958. Unpublished office report on file with the USDA Forest Service, Southern Research Station, Monticello, AR 7 1656.

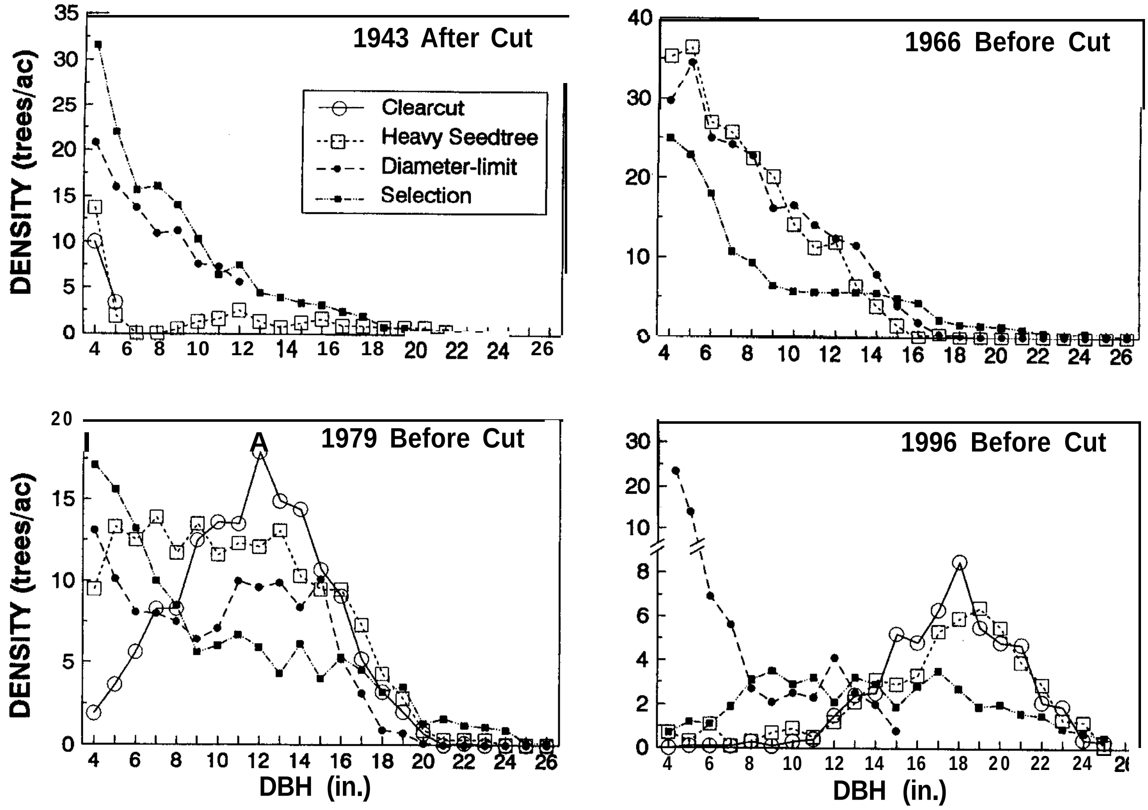

Figure 1. Diameter distribution of loblolly-shortleaf pines managed under four reproduction cutting methods through 53 yr. In 1968, clearcut plots were not measured.

Heavy Seedtree Cut

In 1943, this method of cut reduced the pine component to a residual density averaging 13 seedtrees/ac that were greater than 9 in. dbh (Figure 1). Another 18 pines/ac, 3.6 to 8.5 in. dbh, remained on the plots. Seedtrees averaged 17 ft^2/ac in basal area, 480 ft^3/ac in merchantable volume, and 1,700 bd ft/ac in sawlog volume. In 1968, which was 25 yr after the initial cut and 10 yr after seedtrees were removed, the diameter distribution had an uneven-aged structure which persisted through 1979 (Figure 1). By 1996, a normal even-aged distribution had developed.

During 53 yr of management, PA1 in basal area on these plots equaled ($P > 0.05$) or exceeded (PI 0.01) basal area growth on diameter-limit and selection cutting methods (Table 1). Because seedtrees were left on the plots for 15 yr, they made a substantial contribution to PA1 in sawlog volume (bd ft/ac), which was 212% greater ($P < 0.01$) than on clearcut plots between yr 10 and 15. Total merchantable volume peaked in 1979, but sawlog volume (both ft^3/ac and bd ft/ac) increased through 53 yr of management (Figure 2). Because of only one commercial thinning during the first 15 yr, PA1 in merchantable volume was significantly greater ($P < 0.01$) between yr 25 and 36 when compared to diameter-limit or selection plots (Table 1). During the same 11 yr, seedtree plots had the highest ($P < 0.01$) PA1 in sawlog volume (148 ft^3/ac and 715 bd ft/ac), and those values averaged greater than for any other growth interval or cutting method through 53 yr.

Merchantable volume production through 53 yr averaged 5,600 ft^3/ac, which was better ($P < 0.01$) than the diameter-limit and selection methods (Table 2). For sawlog volume in ft^3/ac, there was no difference ($P = 0.07$) in total production among cutting methods through 53 yr, but sawlog volume in bd ft/ac averaged 51% higher ($P < 0.01$) on seedtree plots compared to diameter-limit plots (Table 2).

Diameter-Limit Cut

This method of cut has a notoriously bad reputation because it is often associated with high-grading-when all better-quality trees are removed during harvest and trees of poorest quality are left. However, in the present study, there was strict adherence to removing all pines greater than 11.5 in. dbh, regardless of quality. Following the initial diameter-limit cut in 1943, residual density averaged 93 pines/ac with 25 ft^2/ac in basal area and 520 ft^3/ac in merchantable volume. Throughout 53 yr of management, this cutting method resulted in an uneven-aged structure (Figure 1).

During the first 25 yr, PA1 in basal area on diameter-limit plots was no different ($P > 0.05$) than on the heavy seedtree cutting method (Table 1). At no time was basal area growth on diameter-limit plots less than on selection plots. Between yr 36 and 43, basal area growth was lowest compared to any other growth interval, averaging less than 1 $ft^2/ac/yr$ as ingrowth from pine regeneration because of the heavy cut (>1,000 ft^3/ac) following more than 11 yr without thinning (Figure 2).

Compared to the other three cutting methods, diameter-limit plots exhibited the lowest standing volumes through time (Figure 2). Still PA1 in merchantable volume was either greater than ($P < 0.05$) or equal to ($P > 0.05$) PA1 on selection plots for 53 yr (Table 1). PA1 for sawlog volume production

Table 1. Periodic annual increment of natural loblolly-shortleaf pines during 53 yr of management under four reproduction cutting methods.

Growth interval (yr)	Reproduction cutting methods: Clearcut	Heavy seedtree	Diameter limit	Selection	Mean square error	$P > F$
	........[Basal	area (ft²/ac/yr)]........				
o-5	0.20b*	0.98a	1.22a	1.13a	0.088	0.01
5-10	4.10a	3.21a	3.39a	3.21a	0.765	0.57
10–15	9.54a	5.73b	3.76b	3.43b	1.273	co.01
15–20	—†	5.13a	5.34a	2.531,	0.444	co.01
20–25	—†	6.73a	6.12a	3.76a	1.568	0.06
25-36	—†	4.12a	3.05b	2.46c	0.064	co.01
36–43	3.16a	2.40a	0.87b	1.22b	0.140	co.01
4348	2.17a	2.08a	1.75a	1.46a	0.483	0.60
48-53	2.28a	1.57a	2.05a	1.45a	0.373	0.46
	.... [Merchantable volume (ft³/ac/yr)]					
0-5	5c	28b	44ab	50a	65	co.01
5-10	52b	69ab	90a	96a	197	0.02
10–15	183a	112b	85b	102b	522	co.01
15-20	—†	124a	149a	74b	272	co.01
20-25	—†	183a	173a	102b	929	0.03
25-36	—†	149a	105b	81c	71	co.01
36–43	109a	86a	37b	54b	121	co.01
43-48	76a	73a	59a	56a	493	0.61
48-53	82a	59a	43a	57a	234	0.11
	.... [Sawlog volume (ft³/ac/yr)‡]					
o-5	0c	25b	42a	52a	42	co.01
5-10	3d	36c	66b	80a	29	<0.01
10–15	23b	44b	44b	86a	304	0.01
15-20	—†	34c	76a	59b	70	co.01
20-25	—†	107a	123a	71b	245	0.02
25-36	—†	148a	106b	73c	94	co.01
36-43	106a	87a	42b	60b	83	co.01
4348	75a	71a	56a	61a	389	0.61
48-53	81a	65ab	28b	67ab	219	0.02
	.... [Sawlog volume (bd ft/ac/yr)§]					
o-5	0c	148b	158b	260a	843	co.01
5-10	llc	225b	274b	407a	579	co.01
10–15	90c	281ab	166bc	434a	5,926	co.01
15-20	—†	133b	288a	302a	973	co.01
20-25	—†	411a	504a	402a	3,886	0.16
25-36	—†	715a	465b	415b	2,066	co.01
36-43	619a	533a	180c	355b	2,051	co.01
4348	494a	466a	256a	350a	10,245	0.07
48-53	584a	489a	109b	409a	5,458	co.01

* Row means for periodic annual increment that are followed by the same letter are not significantly different at the 0.05 level.
† No data available.
‡ Periodicannualincrementforsawtimbercubicfeetoccasionallvexceedsthatfortotal merchantablecubicfeetbecauseofsawtimber ingrowth (Murphy and Shelton 1994).
§ Doyle log scale.

(both ft³/ac and bd ft/ac) peaked during the 20-25 yr growth interval probably because pulpwood-sized pines had rapid diameter growth as they developed into sawlog size. From yr 15 to 36, PA1 in sawlog volume (bd ft/ac) on diameter-limit plots was no different ($P > 0.05$) than occurred on selection plots (Table 1).

For the first 10 yr, total production in merchantable volume on diameter-limit plots was better than ($P < 0.01$) that on clearcut plots, but during the next 43 yr, merchantable volume production was no different ($P > 0.05$) compared to the clearcut method (Table 2). Between yr 5 and 25, diameter-limit plots also produced more ($P < 0.01$) sawlog volume (ft³/ac) than the even-aged cutting methods, and during the next 28 yr, sawlog production was equal ($P > 0.05$) to the seedtree plots (Table 2). With the exception of yr 15, sawlog production (ft³/ac) on diameter-limit plots was no less ($P > 0.05$) than occurred on selection plots throughout 53 yr. Other than at yr 36, diameter-limit plots produced less ($P < 0.01$) sawlog volume (bd ft/ac) than selection plots throughout 53 yr of management (Table 2).

Selection Cut

In 1943, the initial selection cut left an average of 145 merchantable-sized pines/ac with 56 ft²/ac of basal area, 1,400 ft³/ac in merchantable volume, and 3,300 bd ft/ac in sawlog volume. After harvest, the diameter distribution exhibited a reversed-J (negative exponential) pattern (Figure 1)

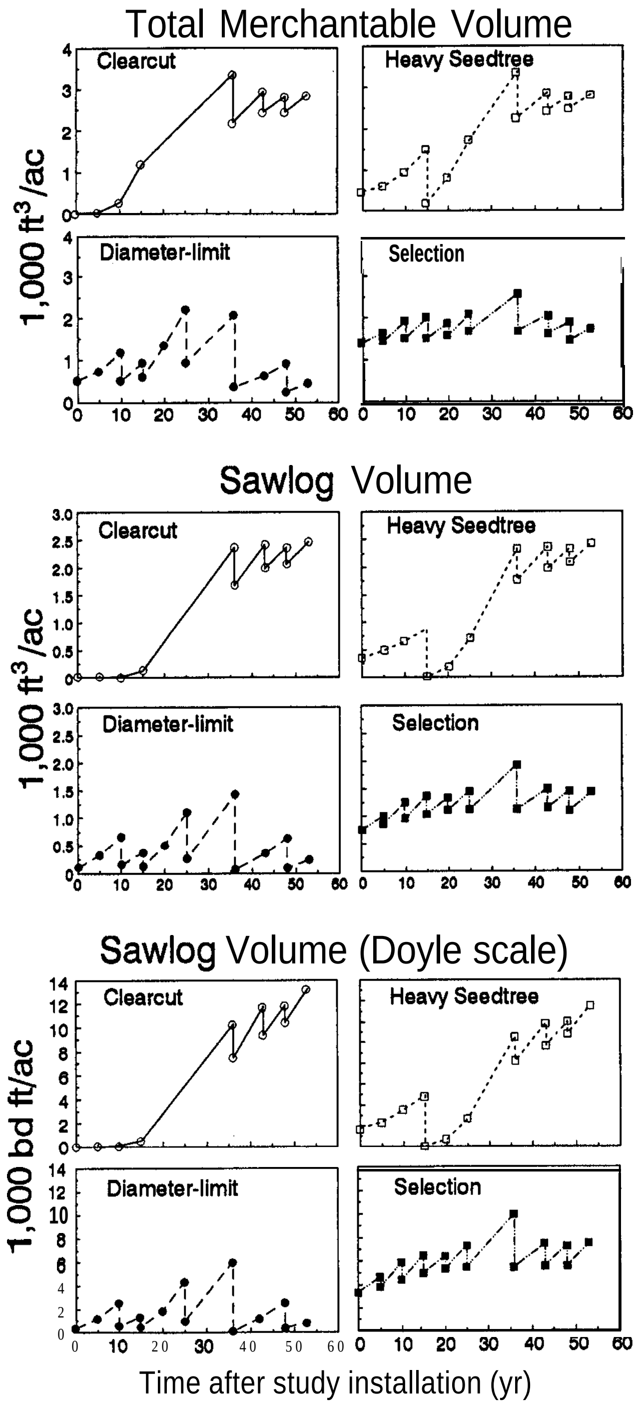

Figure 2. Standing volume in loblolly-shortleaf pines before and after harvest through 53 yr of management under four reproduction cutting methods.

typical of uneven-aged stands. A similar structure was apparent in 1968 and 1979, but by 1996, a normal diameter distribution had developed (Figure 1) due to lack of pine ingrowth from submerchantable size classes. During six out of nine growth intervals through 53 yr of management, PA1 in stand basal area on selection plots was no different ($P > 0.05$) than the seedtree cutting method (Table 1). A similar pattern was evident when selection plots were compared to the diameter-limit plots with seven of nine growth intervals having comparable ($P > 0.05$) PA1 in basal area. Standing merchantable volume and sawlog volume were highest on selection plots after 36 yr of management because more than 10 yr had past since the last cut (Figure 2), otherwise cut volumes tended to equal periodic growth.

Because of the high residual pine basal area stocking on selection plots after the 1943 harvest, PA1 in merchantable volume exceeded ($P < 0.01$) that from either of the even-aged treatments during the first 5 yr of management (Table 1). During the next 10 yr, PA1 in merchantable volume on selection plots was no different from seedtree or diameter-limit plots. Between 15 and 43 yr, selection plots had less ($P \leq 0.03$) PA1 in merchantable volume than the even-aged cutting methods, but during the last 10 yr, PA1 in merchantable volume was no different ($P > 0.05$) among cutting methods.

For PA1 in sawlog-sized pines, selection cutting resulted in better ($P \leq 0.01$) volume growth (ft^3/ac) compared to the even-aged cutting methods during the first 20 yr because sawlog-sized pines were retained as growing stock on selection plots (Table 1). Then from 20 yr through 36 yr, PA1 in sawlog volume (ft^3/ac) was less ($P \leq 0.02$) compared to the seedtree and diameter-limit cutting methods. During the last 17 yr, PA1 in sawlog volume (ft^3/ac) for selection cutting was either less than ($P \leq 0.05$) or equal ($P > 0.05$) to that of the other three cutting methods. For the first 20 yr after study initiation, PA1 for sawlog volume (bd ft/ac) averaged higher on selection plots compared to the other cutting methods, but mean differences were not always statistically significant (Table 1). During the next 33 yr, PA1 in sawlog volume (bd ft/ac) on selection plots averaged less than ($P < 0.05$) or equal to ($P > 0.05$) the even-aged cutting methods. During the last 5 yr, selection exceeded ($P < 0.01$) diameter-limit PA1 by 300 bd ft/ac/yr.

During the first 10 yr, total production in merchantable volume on selection plots was 90% greater ($P < 0.01$) than on even-aged plots but no different ($P > 0.05$) than on diameter-limit plots (Table 2). By yr 25, merchantable volume production on selection plots had declined and was 20% less ($P = 0.02$) than the seedtree and diameter-limit plots. For the last 28 yr, merchantable volume continued to average significantly less (P c 0.01) on selection plots compared to other cutting methods. During the last 10 yr of management, merchantable volume on even-aged cutting methods exceeded ($P < 0.01$) that on selection plots by more than 1,000 ft^3/ac (Table 2).

Sawlog volume production (ft^3/ac) on selection plots always averaged higher than other cutting methods during the first 20 yr, although differences were not always statistically significant (Table 2). By yr43, sawlog productivity (ft^3/ac) began to average less on selection plots compared to the other cutting methods, but there were no statistically significant differences ($P > 0.05$) among cutting methods after 53 yr of management (Table 2). During the first 25 yr, volume production (bd ft/ac) on selection plots exceeded ($P < 0.01$) all other cutting methods (Table 2). By yr 36, sawlog production (bd ft/ac) on seedtree and diameter-limit plots had caught up to the selection cutting method, and there were no statistically significant differences ($P > 0.05$) between selection and the even-aged cutting methods during the last 10 yr of management.

Table 2. Total volume production* of natural loblolly-shortleaf pines during periodic growth intervals during 53 yr of management under four reproduction cutting methods.

Years of management	Reproduction cutting methods: Clearcut	Heavy seedtree	Diameter limit	Selection	Mean square error	$P > F$
	[Merchantable volume (1,000 ft^3/ac)]					
5	0.03c[†]	0.14b	0.22ab	0.26a	0.002	co.01
10	0.28c	0.49bc	0.67ab	0.73a	0.009	co.01
15	1.20a	1.05a	1.09a	1.24a	0.027	0.49
20	—[‡]	1.66a	1.84a	1.61a	0.03 1	0.32
25	—[‡]	2.58a	2.70a	2.12b	0.035	0.02
36	3.35b	4.21a	3.851,	3.01c	0.040	co.01
43	4.12b	4.81a	4.11b	3.38c	0.040	co.01
48	4.50b	5.18a	4.41b	3.66c	0.075	co.01
53	4.90ab	5.60a	4.62b	3.80c	0.092	co.01
	[Sawlog volume (1,000 ft^3/ac)]					
5	0.00C	0.13b	0.21a	0.26a	0.001	co.01
10	0.01c	0.31b	0.54a	0.66a	0.003	co.01
15	0.13d	0.52c	0.76b	1.09a	0.010	co.01
20	—[‡]	0.70b	1.14a	1.39a	0.016	co.01
25	—[‡]	1.23b	1.76a	1.74a	0.016	co.01
36	2.36b	2.85a	2.92a	2.54ab	0.033	0.02
43	3.10b	3.46a	3.21ab	2.97b	0.023	0.02
48	3.48ab	3.82a	3.49ab	3.27b	0.043	0.07
53	3.88a	4.23a	3.63a	3.47a	0.059	0.07
	[Sawlog volume (1,000 bd ft/ac)[§]]					
5	0.00C	0.74b	0.79b	1.29a	0.021	co.01
10	0.05c	1.86b	2.16b	3.33a	0.061	co.01
15	0.50c	3.27b	2.99b	5.50a	0.090	<0.01
20	—[‡]	3.93b	4.43b	7.02a	0.098	co.01
25	—[‡]	5.99c	6.95b	9.02a	0.061	co.01
36	10.29b	13.85a	12.06ab	13.59a	0.676	co.01
43	14.63bc	17.58a	13.32c	16.06ab	0.692	co.01
48	17.10bc	19.91a	14.60c	17.81ab	1.322	co.01
53	20.02a	22.83a	15.14b	19.44a	2.102	co.01

* Total volume production at each year = standing volume in merchantable-sized pines + total volume cut - 1943 standing volume in merchantable-sized pines.
† Row means for periodic volume production that are followed by the same letter are not significantly different at the 0.05 level.
‡ No data available.
§ Doyle log scale.

Pine Regeneration and Woody Competition at 55 Years

A 1999 inventory revealed a high density and good distribution of pine seedlings that averaged more than 3,600 stems/ac and greater than 40% stocking across all four cutting methods (Table 3) with no differences among cutting methods in density ($P = 0.64$) or stocking ($P = 0.99$). Since no pine regeneration was needed on the even-aged plots, prescribed burning was used to control competing vegetation. Consequently, pine sapling density was virtually nil on the even-aged plots as a result of periodic burning and the intolerance of pine regeneration to overstory shade.

On the diameter-limit and selection plots, pine regeneration was needed to maintain stand structure, and selective herbicides were used periodically to free these submerchantable pines from competition. Across all pine sapling dbh classes, diameter-limit plots averaged from 3 to 8 times more ($P < 0.01$) saplings compared to selection plots (Table 3). Also, stocking of pine saplings ranged from 2 to 3 times higher ($P < 0.01$) on diameter-limit versus selection plots. Still, density and stocking of pine regeneration were adequate to sustain selection management.

Density and stocking of nonpine woody competition in the seedling size class averaged greater than 8,000 rootstocks/ac and 99%, respectively, and there were no differences ($P = 0.06$) among cutting methods (Table 3). In the sapling size classes, 1 in. nonpine woody stems had the highest density across cutting methods, and diameter-limit plots had 137% more ($P = 0.02$) 1 in. nonpine saplings than the other three cutting methods. For 2 and 3 in. nonpine saplings, there were no differences ($P > 0.05$) in mean density among cutting methods. Moreover, there were no differences ($P > 0.05$) in mean stocking of nonpine woody saplings among the four cutting methods (Table 3).

Density of merchantable-sized hardwoods averaged only 13 trees/ac across cutting methods (Table 4), and mean differences were nonsignificant ($P = 0.21$). Although, hardwood basal area was higher ($P = 0.02$) on clearcut plots when compared to seedtree or selection plots, the clearcut method averaged only 6 ft^2/ac. Clear-cuts also had six times more ($P = 0.01$) hardwood volume in merchantable size classes than the seedtree or selection methods.

Discussion

Each of the four natural reproduction cutting methods reported in this article has advantages and disadvantages in

Table 3. Regeneration of natural loblolly-shortleaf pines and hardwoods after 55 yr of management under four reproduction cutting methods.

Measurement variable and size class	Clearcut	Heavy seedtree	Diameter limit	Selection	Mean square error	P > F
	Reproduction cutting methods					
Pine Density	(number/ac)					
Seedlings	7,250a*	4,710a	1,480a	1,170a	4.2 × 10'	0.64
1 in. saplings	3b	0b	560a	172b	9,597	<0.01
2 in. saplings	0b	0b	267a	33b	2,227	<0.01
3 in. saplings	0b	0b	108a	20b	320	<0.01
Pine stocking†	(percent)					
Seedlings	37a	45a	45a	39a	1,257	0.99
1 in. saplings	1c	0c	71a	40b	67	<0.01
2 in. saplings	0c	0c	65a	25b	31	<0.01
3 in. saplings	0c	0c	55a	16b	29	<0.01
Hardwood density‡	(number/ac)					
Seedlings	9,050a	9,440a	7,280a	6,330a	1.6×10^6	0.06
1 in. saplings	155b	195b	460a	233b	10,064	0.02
2 in. saplings	29a	20a	73a	29a	1,448	0.37
3 in. saplings	0a	5a	13a	5a	44	0.18
Hardwood stocking†	(percent)					
Seedlings	97a	100a	100a	100a	1	0.06
1 in. saplings	53a	64a	91a	72a	235	0.09
2 in. saplings	20a	13a	40a	20a	381	0.42
3 in. saplings	0a	5a	12a	4a	29	0.13

* Row means followed by the same letter are not significantly different at the 0.05 level.
† Based on the presence of at least one seedling or sapling per sampled quadrat.
‡ Includes woody shrubs.

long-term application (Brender et al. 1981, Smith 1986). All have the advantage of low establishment cost when compared to planting, and all have the disadvantage of potential failure if establishment phases coincide with seedcrop deficiency, drought, or excessive competition.

Clearcutting in small blocks or strips of 5 to 10 ac is well suited for loblolly and shortleaf pines when applied to sites surrounded by large trees that regularly produce ample seed (Grano 1954, Cain 1996, 1997). The seedtree method has a built-in seed source that permits harvesting over larger areas than clearcuts, and may result in some genetic improvement if the best pines are left for seed. With both even-aged cutting methods, management operations are concentrated in space and time. These methods generally require a low level of skill, and loggers often view them as the most efficient way of harvesting. On the negative side, landowners have long waiting periods of 15 to 20 yr before the first commercial thinning following reproduction cutting. For seedtree cuts, there is the potential for loss of the seedtrees by lightning, wind, and ice before they are harvested. Also, young pine stands produced by both of these even-aged methods are subject to loss by fire, ice, insects, and disease because of their homogeneity.

In this study, the clearcut method probably ranked lowest in management cost because no vegetation management was applied between 1946 and 1979. After that, nonmerchantable hardwoods were controlled by one herbicide injection treatment, then only prescribed burning was used to control nonpine vegetation during the next 17 yr. Although total sawlog production (ft^3/ac) from these clearcuts was no different ($P > 0.05$) from the other cutting methods through 53 yr, the landowner received no income from commercial thinnings for 38 yr after the initial harvest even though pines had attained merchantable size much earlier.

In the heavy seedtree cutting method, seedtrees were retained for 15 yr after the initial harvest, but they could have been harvested 10 yr earlier because pine regeneration was well established by then. This cutting method resulted in an average production of 23,000 bd ft/ac through 53 yr, which was the highest of all cutting methods and significantly better ($P < 0.01$) than diameter-limit plots. High productivity from the heavy seedtree method reflected growth of residual seedtrees over the 15 yr they were retained on site; their net growth, including sawlog ingrowth and mortality, averaged 210 bd ft/ac/yr. In terms of cost, this method probably ranked slightly above clearcutting because there were management

Table 4. Status of merchantable-sized hardwoods after 55 yr of managing loblolly-shortleaf pines under four reproduction cutting methods.

Merchantable-sized hardwood variables	Clearcut	Heavy seedtree	Diameter limit	Selection	Mean square error	P > F
	Reproduction cutting methods					
Density (stems/ac)	23a*	11a	15a	3a	109.33	0.21
Basal area (ft^2/ac)	6a	2b	3ab	<1b	2.55	0.02
Merchantable volume (ft^3/ac)	107a	30b	43ab	6b	839.09	0.01

* Row means followed by the same letter are not significantly different at the 0.05 level.

expenses associated with seedtree removal and one combined precommercial and commercial thinning during the first 36 yr. Otherwise, expenses for hardwood control paralleled the clearcut method.

Compared to even-aged cutting methods, uneven-aged systems are reputed to be less vulnerable to loss by fire, biotic agents, or climate extremes; provide periodic income to landowners; may result in more favorable tax rates because income is spread through time; and a reserve of large trees is available to take advantage of fluctuating timber prices (Baker and Murphy 1982, Baker et al. 1996). From the standpoint of periodic income to the landowner, both selection cutting and diameter-limit cutting in this study were more favorable than the two even-aged systems because harvesting was done about every 5 to 10 yr, respectively. After 53 yr of management, sawlog volume production in bd ft/ac was 27% less ($P < 0.01$) on diameter-limit plots compared to the other cutting methods, but volume production in ft^3/ac did not differ ($P = 0.07$) among the four cutting methods.

A major disadvantage of uneven-aged cutting methods on good sites (site index 285 ft at 50 yr for loblolly pine) is that both woody and herbaceous competition must be controlled on a regular basis if pine seedlings are to become established and develop into merchantable size classes (Baker et al. 1996, Shelton and Cain 2000). This is best accomplished with selective broadcast herbicides to control both woody and herbaceous competition. In this study, for example, the uneven-aged diameter distribution on selection plots had disappeared by 1996 (Figure 1) because competing vegetation, especially vines, were not adequately controlled between 1968 and 1989. Without competition control, ground cover from herbaceous vegetation on these sites can approach 100% and thereby effectively exclude the establishment of pine regeneration from natural seedfall (Cain 1985, 1991, 1992, 1993).

Another disadvantage of selection cutting is that it requires a high degree of management skill to maintain desirable stand structure. Careful harvest practices must also be used to protect submerchantable-sized pines. Due to these exigent factors, the selection cutting method in this study probably required the highest management costs. Thus, its application is most favorable for landowners that place a high priority on the visual properties of their stands, because a sawtimber component is continuously retained. The method is also suitable for landowners of small acreages who desire sustainable sawtimber production with no lag periods for stand regeneration.

Because of its association with high-grading, diameter-limit cutting is usually not recognized as a viable reproduction cutting method. However, in the present study, diameter-limit cutting involved the removal of all trees above a certain dbh, regardless of tree quality; therefore, high-grading was not a concern. According to Murphy and Shelton (1990), if diameter-limit cutting is done regularly and consistently in loblolly-shortleaf pine stands, the stands will recover from the initial reduction in growing stock and will produce a sustainable harvest. In this study, pine diameter distribution on diameter-limit plots exhibited a reversed-J structure throughout 53 yr (Figure 1), and had better uneven-aged diameter distribution in 1996 than did the selection plots. Since less technical skill was needed to manage diameter-limit cutting, cost probably ranked less than selection cutting but higher than clearcutting or seedtree cutting because of numerous stand entries for harvest and competition control.

Competition control is a necessary part of natural reproduction cutting methods if they are to be successful on good sites. The most obvious indicator of that need in this study was the collapse of uneven-aged structure in merchantable size classes on selection plots, when measurements were taken after 53 yrof management (Figure 1). Even so, the most recent regeneration survey suggests that selection plots have adequate density and stocking in pine seedlings and saplings as long as they are kept free-to-grow from herbaceous and woody nonpine vegetation and are not destroyed during harvest operations. Also, preharvest and postharvest merchantable basal area of loblolly and shortleaf pines must be bracketed within published guidelines (e.g., 75 and 60 ft^2/ac, respectively, on a 5 yr cutting cycle) for selection management if pine seedlings and saplings are to attain merchantable size (Baker et al. 1996, Farrar 1996).

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