Postthinning growth and yield of row-thinned and selectively thinned loblolly and slash pine plantations

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This study compared growth responses in planted loblolly pine (*Pinus taeda* L.) and slash pine (*P. elliottii* Engelm.) stands thinned by using three row-felling methods and at the same density levels, three selective felling methods. The study plots were in six plantations, aged 15–22 years, located in central Louisiana. Growth was measured 5 and 10 years after plot installation. Site index varied from 19.5 to 31.7 m (base age 50) and initial planting densities ranged from 1993 to 2989 trees/ha. Study results show there will likely be less diameter increment and less net basal area and cubic-metre volume per unit area growth and yield, and the growth will be in smaller-sized trees, if row thinning is used rather than selective thinning from below. These differences will probably be greater in slash pine plantations than in loblolly pine plantations.

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Cette étude visait à comparer la réponse de la croissance de peuplements artificiels de Pin loblolly (*Pinus taeda* L.) et de Pin à encens (*P. elliottii* Engelm.) éclaircis suivant trois méthodes en rangée et, en maintenant la même densité résiduelle, suivant trois méthodes sélectives. Les places d'étude étaient localisées dans six plantations âgées de 15 à 22 ans et situées dans le centre de l'État de Louisiane. La croissance a été mesurée 5 et 10 ans après l'établissement des places. L'indice de qualité de station variait de 19,5 à 31,7 m à l'âge de référence de 50 ans et la densité initiale de plantation variait de 1993 à 2989 arbres/ha. Les résultats de cette étude indiquent que la croissance en diamètre et que la croissance et la production nette en surface terrière et en volume à l'hectare seront vraisemblablement moindres, et que la croissance sera concentrée sur les plus petits arbres si l'on éclaircit par rangées plutôt que sélectivement par le bas. Ces différences seront apparemment plus considérables avec les plantations de Pin à encens qu'avec celles de Pin loblolly.

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Introduction

Forest stands can be thinned in numerous ways. In plantations, two major thinning methods can be easily defined: (*i*) in row or corridor thinning, all trees in certain rows or swaths are removed; and (*ii*) in selective thinning, trees are chosen for felling according to certain criteria.

Many studies have been performed and articles written concerning the economic and silvicultural advantages of each of these two broad methods (e.g., Enghardt 1969; Bennett 1971; Anonymous 1971; Williston 1972; Hamilton 1976; Scott 1977; Wright 1976). For loblolly pine (*Pinus taeda* L.) and slash pine (*P. elliottii* Engelm.), no studies have quantified by certain useful aspects the growth differences that can be expected after thinning by alternative methods. These aspects deal with equivalent basal-area levels in stands covering a range of site indices, initial planting densities, and different ages at first thinning. For example, studies of loblolly pine by Grano (1971), Williston (1967), and Bredenkamp (1984) involved tests of alternative thinning methods only in plantations with the same age, location, and planting spacing. These limitations appear to apply to studies of other species. Only one spacing, age, and location were used for the studies by Jensen and Pelz (1977) of red pine (*P. resinosa* Ait.) and by Cremer and Meredith (1974) of radiata pine (*P. radiata* D. Don).

The objectives of this study were to compare the results of row thinning and selective thinning for slash and loblolly pine plantations from the following perspectives: cubic-metre volume, basal area (at 1.4 m above ground line), and diameter growth and yield (at 1.4 m above ground line). Plantations are at different locations, with various ages, site indices, and initial planting densities, and their stocking levels after thinning are comparable. The study also determined how diameter distributions are affected by the two thinning methods.

Materials and methods

Data for this study were obained from plots established in six plantations at five locations in central Louisiana. Basic prethinning data were as follows:

Location	Pine species	No. of trees planted/ha	Before-thinning trees surviving at installation (trees/ha)	Age at start of study (yr)
McNary	Slash	2243	1596	15
Melder	Loblolly	2989	2333	15
Pollock	Slash	2243	1404	17
Leesville	Loblolly	1993	1747	20
Hineston	Loblolly	2989	2120	21
Hineston	Slash	2989	2031	22

When this study started, average tree survival at the sites ranged from 63 to 88%. Fusiform rust (*Cronartium quercuum* (Berk.) Miyabe ex Shirai f.sp. *fusiforme*) stem infection rates averaged less than 15% at all loblolly pine plantations and at the Pollock slash pine plantation. Infection rates at the Hineston and McNary slash pine plantations averaged 29 and 22%, respectively.

Estimated site index (base age 50) for the slash pine plantations averaged 30 m and ranged from 26 to 32 m on individual study

TABLE 1. Comparison of average yields of growing stock of planted loblolly pine, immediately after either the first row thinning or selective thinning, and with no thinning

Thinning treatment	Dominant–codominant ht. (m)	No. of trees surviving/ha	Quadratic mean dbh (cm)	Net basal area (m^2/ha)	Net inside-bark vol. (m^3/ha)
A-1	14.9	1077	15.7	21.3	135.0
B-1	14.9	909	17.3	21.3	144.1
Difference	0	168	−1.6	0	−9.4
EMS	0.38558	20 672.54	0.42664	5.03340	485.457
F	0	2.75	10.00	0.01	0.34
P	1.0	0.1136	0.0051	0.9715	0.5669
A-2	14.6	1310	15.5	24.8	154.9
B-2	15.5	964	18.3	24.9	164.0
Difference	−0.7	347	−2.8	−0.1	−9.1
EMS	0.38558	20 672.54	0.42664	5.03340	485.457
F	3.64	11.66	53.34	0.01	0.34
P	0.0715	0.0029	0.0001	0.9431	0.5684
A-3	14.6	1586	14.7	26.9	162.6
B-3	15.3	1223	17.0	26.9	176.5
Difference	−0.7	363	−2.3	0	−13.9
EMS	0.38558	20 672.54	0.42664	5.03340	485.457
F	3.01	12.81	23.16	0.00	0.80
P	0.0989	0.0020	0.0001	1.0000	0.3826
[(A-1) + (A-2) + (A-3)]/3	14.7	1324	15.3	24.3	150.8
[(B-1) + (B-2) + (B-3)]/3	15.2	1032	17.5	24.4	161.5
Difference	−0.5	292	−2.2	−0.1	−10.7
EMS	0.38558	20 672.54	0.42664	5.03340	485.457
F	4.43	24.95	63.01	0.00	1.41
P	0.0489	0.0001	0.0001	0.9507	0.2496
[(A-1) + (A-2) + (A-3) + (B-1) + (B-2) + (B-3)]/6	15.0	1178	16.4	24.4	156.2
C	14.8	2051	15.5	37.8	239.2
Difference	0.2	−873	0.9	−13.4	−83.0
EMS	0.38558	20 672.54	0.42664	5.03340	485.457
F	0.32	12.12	8.64	122.70	48.68
P	0.5766	0.0011	0.0084	0.0001	0.0001

NOTE: Thinning treatments are as follows: A-1, remove 1 row in 2; B-1, select to the same basal area; A-2, remove 1 row in 3; B-2, select to the same basal area; A-3, remove 1 row in 4, then 1 row in 3; B-3, select to the same basal area; C, leave stand unthinned. EMS, error mean square; *F*, computed Fisher's *F*-ratio; *P*, significance associated with *F*. Degrees of freedom were as follows: total = 27; error = 19; model = 8 (block = 2; treatments = 6).

plots. For the loblolly plantations, site index averaged 25 m and ranged from 20 to 29 m on individual plots.

Study plot area varied according to the planting spacing. Rectangular treatment plots contained a center measurement area 12 rows wide × 20.1 m long. Isolation strips surrounding the center plots were four rows wide on each side × 10.05 m wide at each end. Thus, each gross plot was 20 rows wide × 40.2 m long.

The following six thinning treatments and an unthinned control were included in each study plantation:

A. Row-thinning methods
   1. One in two: clear-cut every other row with no other thinning.
   2. One in three: clear-cut every third row with no other thinning.
   3. One in four: clear-cut every fourth row initially and cut center row of remaining three rows 5 years later.

B. Selective thinning methods
   1. Residual basal area after thinning ±0.28 m^2 of A-1. Thin once.
   2. Residual basal area after thinning ±0.28 m^2 of A-2. Thin once.
   3. Residual basal area after thinning initially, and 5 years later, both thinnings to within ±0.28 m^2 of each respective A-3 thinning. A total of two thinnings.

C. Unthinned control

Selective thinning methods were carried out primarily from below. Dominants were cut only when rough, defective, forked, or diseased, or when their removal helped adjacent dominants or codominants.

Overall, the study had a randomized block experimental design, with each location considered to be a separate block. Within the block, treatments were randomly assigned to individual plots. The overall design was unbalanced because more than one treatment replication was not possible at some locations. The slash pine plantations at McNary had three replications of all treatments, the loblolly pine plantation at Hineston had two replications, and all others had only one replication.

Plot and tree measurements were made initially, and in the 5th and 10th years following the first thinning, to determine changes in volume, diameter, basal area and dominant–codominant height, growth and yield, mortality, and diameter distributions.

TABLE 2. Comparison of average yields of growing stock of planted slash pine, immediately after either the first row thinning or selective thinning, and with no thinning

Thinning treatment	Dominant-codominant ht. (m)	No. of trees surviving/ha	Quadratic mean dbh (cm)	Net basal area (m^2/ha)	Net inside-bark vol. (m^3/ha)
A-1	15.5	813	16.8	17.6	109.1
B-1	15.4	655	18.5	17.4	112.2
Difference	0.1	158	−1.7	0.2	−3.1
EMS	0.41789	12 986.76	0.80393	8.36978	654.413
F	0.04	4.34	13.61	0.02	0.09
P	0.8522	0.0472	0.0010	0.8961	0.7699
A-2	15.4	1060	16.5	22.7	138.1
B-2	15.7	956	17.5	22.5	138.6
Difference	−0.3	104	−1.0	0.2	−0.5
EMS	0.41789	12 986.76	0.80393	8.36978	654.413
F	0.89	2.89	4.90	0.01	0.00
P	0.2554	0.1011	0.0358	0.9220	0.9651
A-3	15.1	1238	16.3	25.3	150.1
B-3	15.6	1023	17.8	25.2	160.6
Difference	−0.5	215	−1.5	0.1	−10.5
EMS	0.41789	12 986.76	0.80393	8.36978	654.413
F	2.87	8.35	11.38	0.00	1.01
P	0.1023	0.0077	0.0023	0.9739	0.3239
[(A-1) + (A-2) + (A-3)]/3	15.3	1037	16.5	21.9	132.4
[(B-1) + (B-2) + (B-3)]/3	15.6	878	17.9	21.7	137.1
Difference	−0.3	159	−1.4	0.2	−4.7
EMS	0.41789	12 986.76	0.80393	8.36978	654.413
F	1.99	14.84	28.69	0.02	0.60
P	0.1697	0.0007	0.0001	0.8801	0.4444
[(A-1) + (A-2) + (A-3) + (B-1) + (B-2) + (B-3)]/6	15.5	985	17.2	21.8	134.8
C	15.4	1680	16.0	33.8	203.7
Difference	0.1	−695	1.2	−12.0	−68.9
EMS	0.41789	12 986.76	0.80393	8.36978	654.41
F	0.14	161.60	9.50	127.30	74.30
P	0.7147	0.0001	0.0048	0.0001	0.0001

NOTE: For explanation of thinning treatments and definitions of abbreviations see Table 1. Degrees of freedom were as follows: total = 34; error = 26; model = 8 (block = 2; treatments = 6).

Plot basal areas were measured using all plot trees. Volumes were determined from a subset of those trees, which were chosen proportionately from each diameter class according to numbers within each class. The volumes of these selected trees were estimated by the height accumulation technique computerized by Lohrey and Dell (1969). Plot cubic-metre volumes were estimated from volume - basal area ratios.

The following procedure was used to estimate volume losses due to mortality for each growth period:

1. The volumes and diameters of the subset sample trees at the previous measurement were obtained from the height accumulation output for plots where mortality had occurred.
2. A linear regression was determined for the individual plots, using the diameter squared of the sample trees as the independent variable and the volumes of these trees as the dependent variable.
3. Inserting into the regression equation the diameter squared from the previous measurement of trees that died, and solving for the dependent variable, gave an estimate of the volumes of dead trees at the time of previous measurement. These estimates were then used as estimates of mortality volumes for each measurement period. Thus, they represent minimum volume losses for the time periods.

The statistical analysis used procedures for an unbalanced randomized complete block design. Selected treatments were compared using the individual degree of freedom procedure. Treatments were compared within each species. Between-species statistical comparisons were not made. The only individual treatment comparisons made (which were determined beforehand) were as follows: A-1 vs. B-1; A-2 vs. B-2; A-3 vs. B-3; [(A-1) + (A-2) + (A-3)]/3 vs. [(B-1) + (B-2) + (B-3)]/3; and [(A-1) + (A-2) + (A-3) + (B-1) + (B-2) + (B-3)]/6 vs. C. The null hypothesis tested in each comparison was that there was no difference between the mean values of the characteristics measured. Probabilities of statistical significance (P) are given where appropriate in the following sections and in Tables 1-8. Decisions about the significance of the numerical treatment mean differences are generally left to the reader.

Results

Thinned versus unthinned stand treatment

Even though the emphasis of this study was to compare row-thinning and selective thinning treatments, results for the unthinned condition are reported as a useful point of reference. The only statistical comparison made dealt with

TABLE 3. Comparison of average yields of growing stock of planted loblolly pine 10 years after either row thinning or selective thinning, and with no thinning

Thinning treatment	Dominant-codominant ht. (m)	No. of trees surviving/ha	Quadratic mean dbh (cm)	Net basal area (m²/ha)	Net inside-bark vol. (m³/ha)
A-1	19.2	848	20.6	28.1	234.6
B-1	19.0	852	21.6	30.7	254.6
Difference	0.2	−4.0	−1.0	−2.6	−20.0
EMS	0.42724	10 079.42	0.69968	10.34563	816.924
F	0.24	0.01	2.59	1.35	0.99
P	0.6269	0.9248	0.1247	0.2608	0.3331
A-2	18.3	1053	19.8	31.9	259.5
B-2	20.0	892	22.4	34.5	290.4
Difference	−1.7	161	−2.6	−2.6	−30.9
EMS	0.42724	10 079.42	0.69968	10.34563	816.924
F	13.16	5.12	18.44	1.29	2.33
P	0.0019	0.0363	0.0004	0.2710	0.1444
A-3	17.5	835	18.5	22.8	190.3
B-3	19.1	630	22.1	22.5	203.1
Difference	−1.6	205	−3.6	0.3	−12.8
EMS	0.42724	10 079.42	0.69968	10.34563	816.924
F	11.99	8.30	37.45	0.03	0.40
P	0.0028	0.0100	0.0001	0.8617	0.5354
[(A-1) + (A-2) + (A-3)]/3	18.3	912	19.6	27.6	228.1
[(B-1) + (B-2) + (B-3)]/3	19.4	791	22.0	29.2	249.4
Difference	−1.1	121	−2.4	−1.6	−21.3
EMS	0.42724	10 079.42	0.69968	10.34563	816.924
F	14.50	8.49	48.19	1.50	3.31
P	0.0013	0.0093	0.0001	0.2367	0.0854
[(A-1) + (A-2) + (A-3) + (B-1) + (B-2) + (B-3)]/6	18.9	852	20.8	28.4	238.8
C	18.1	1517	18.5	41.1	328.3
Difference	0.8	−665	2.3	−12.7	−89.5
EMS	0.42724	10 079.42	0.69968	10.34563	816.924
F	2.24	117.20	18.51	41.25	28.33
P	0.1521	0.0001	0.0004	0.0001	0.0001

NOTE: For explanation of thinning treatments and definitions of abbreviations see Table 1. Degrees of freedom were as follows: *total* = 26; *error* = 18; *model* = 8 (*block* = 2; *treatments* = 6).

average volume. Each of the variables measured over all the thinnings was compared with the appropriate average for the unthinned treatment. The results are given in Tables 1–8.

The patterns of the yield statistics meet expectations for the beginning and end of multiple-year growth periods. For example, because selective thinning was from below, the quadratic mean diameter after thinning of the trees was about 1 cm more than the average for trees in unthinned stands for both species. After 10 years of growth, the difference had increased to more than 2 cm for both species. Net basal area, number of trees surviving, and net inside-bark cubic-metre volume were greater in the unthinned stands at the beginning and end of the growth period. Mean heights of the dominant and codominant trees did not differ much between the thinned and unthinned stands immediately after thinning. However, 10 year later, loblolly pine dominants and codominants in thinned stands were taller, but the opposite was true of slash pines.

Over the 10-year period, periodic annual increment (PAI) for all trees per hectare, and for the 125 largest trees, and the basal-area growth per hectare, were greater in thinned than in unthinned stands (Tables 5–8). Average cubic metre volume growth per hectare was slightly higher in unthinned loblolly pine stands than in thinned stands, but there was a greater difference in slash pine plantations. Both species experienced less mortality according to all measures (trees per hectare, basal area per hectare, and volume per hectare) in thinned than in unthinned stands.

Row-thinning versus selective thinning treatments

For both species, the quadratic mean diameter was greater after selective thinning than after row thinning, and the differences were about the same after 10 years of growth. At the beginning of the period the mean differences were 2.2 cm ($P = 0.0001$) for loblolly pine and 1.4 cm ($P = 0.0001$) for slash pine. Ten years later the differences were 2.4 ($P = 0.0001$) and 1.8 cm ($P = 0.0001$), respectively.

Selective thinning from below removes more trees than does row thinning, because the selection process requires more smaller trees to meet the targeted leave-tree basal area. After thinning, the mean difference in leave-tree density between row-thinned and selectively thinned stands was 292 trees/ha (28% difference, $P = 0.0001$) for loblolly pine and 159 trees/ha (18% difference, $P = 0.007$) for slash

TABLE 4. Comparison of average yields of growing stock of planted slash pine 10 years after either row thinning or selective thinning, and with no thinning

Thinning treatment	Dominant-codominant ht. (m)	No. of trees surviving/ha	Quadratic mean dbh (cm)	Net basal area (m^2/ha)	Net inside-bark vol. (m^3/ha)
A-1	21.2	467	24.1	21.1	178.3
B-1	22.3	561	25.4	27.5	245.3
Difference	−1.1	−94	−1.3	−6.4	−67.0
EMS	0.50038	13 256.50	1.43735	14.64486	1297.753
F	5.37	1.68	2.81	7.06	8.65
P	0.0287	0.2063	0.1059	0.0133	0.0068
A-2	21.1	736	21.8	27.6	233.2
B-2	21.9	798	22.6	31.3	270.9
Difference	−0.8	−62	−0.8	−3.7	−37.7
EMS	0.50038	13 256.50	1.43735	14.64486	1297.753
F	3.64	0.69	0.65	2.36	2.72
P	0.0675	0.4152	0.4287	0.1364	0.1108
A-3	20.7	588	21.8	21.9	175.6
B-3	23.2	455	25.1	22.3	202.4
Difference	−2.5	133	−3.3	−0.4	−26.8
EMS	0.50038	13 256.50	1.43735	14.64486	1297.753
F	6.70	3.41	17.81	0.02	1.39
P	0.0156	0.0763	0.0003	0.8805	0.2496
[(A-1) + (A-2) + (A-3)]/3	−21.0	5.97	22.6	23.5	195.7
[(B-1) + (B-2) + (B-3)]/3	22.5	605	24.4	27.0	239.5
Difference	−1.5	−8	−1.8	−3.5	−43.8
EMS	0.50038	13 256.50	1.43735	14.64486	1297.753
F	15.47	0.03	14.96	6.29	11.09
P	0.0006	0.8736	0.0007	0.0187	0.0026
[(A-1) + (A-2) + (A-3) + (B-1) + (B-2) + (B-3)]/6	21.7	601	23.5	25.3	217.6
C	22.1	1095	20.8	37.0	324.2
Difference	−0.4	−49.4	2.7	−11.7	−106.6
EMS	0.50038	13 256.50	1.43735	14.64486	1297.753
F	3.40	79.09	22.44	40.18	37.52
P	0.0767	0.0001	0.0001	0.0001	0.0001

NOTE: For explanation of thinning treatments and definitions of abbreviations see Table 1. Degrees of freedom were as follows: total = 34; error = 26; model = 8 (block = 2; treatments = 6).

pine.[1] Ten years later the respective differences were 121 (15% difference, $P = 0.0093$) and 8 trees/ha (1% difference, $P = 0.8736$). This indicated that for slash pine, proportionately greater mortality had occurred in the row-thinned stands than in the selectively thinned stands over that time period.

Of course, all row-thinning and selective thinning treatment combinations started out, by design, with the same basal area per hectare. At the end of the 10-year period, selectively thinned loblolly pine stands had only 1.6 m^2/ha more basal area than did row-thinned stands (6% difference, $P = 0.2367$). However, selectively thinned slash pine stands had 3.5 m^2/ha more basal area than the row-thinned stands (13% difference, $P = 0.0187$).

Net cubic-metre volumes per hectare, for both species, were not much different at the start of the growth periods (10.7 m^3/ha, 7% difference, $P = 0.2496$ for loblolly pine; 4.7 m^3/ha, 4% difference, $P = 0.4444$ for slash pine). After 10 years the selectively thinned stands of both species produced the greater volumes (21.3 m^3/ha, or 9% more ($P = 0.0854$), for loblolly pine; 43.8 m^3/ha, or 22% more ($P = 0.0026$), for slash pine).

Mean heights of dominant and codominant trees of both species were different between the row-thinning and selective thinning treatments at both the beginning and end of the measurement period. Dominant and codominant loblolly pines in selectively thinned stands were an average of 0.5 m taller ($P = 0.489$) initially and 1.1 m taller ($P = 0.0013$) after 10 years than equivalent trees in row-thinned stands. For dominant and codominant slash pines the advantage for selectively thinned stands was 0.3 m ($P = 0.1697$) at the beginning of the measurement period and 1.5 m ($P = 0.0006$) at the end.

PAI of all trees was better in selectively thinned stands than in row-thinned stands (Tables 5 and 6). Over all thinning treatments, the average dbh growth advantage for selectively thinned compared with row-thinned leave trees was 0.05 cm/tree per year (17% difference, $P = 0.0003$) for loblolly pine and 0.07 cm/tree per year (15% difference, $P = 0.0001$) for slash pine.

[1]In all cases, percentages indicate differences from the treatment mean that produced the least amount of growth or yield for the characteristic measurement.

TABLE 5. Comparison of average annual growth responses over two 5-year measurement periods for planted loblolly pine following row thinning or selective thinning

Thinning treatment	Diameter increment, all trees ($cm \cdot yr^{-1}$)	Diameter increment, 125 largest trees ($cm \cdot yr^{-1}$)	Dominant–codominant ht. growth ($m \cdot yr^{-1}$)	Net basal-area growth ($m^2 \cdot ha^{-1} \cdot yr^{-1}$)	Net total inside-bark vol. growth ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)
A-1	0.33	0.65	0.3	0.7	9.7
B-1	0.34	0.57	0.4	0.9	11.1
Difference	−0.01	0.08	−0.1	−0.2	−1.4
EMS	0.00303	−0.1129	0.00625	0.05525	13.85268
F	0.21	2.6	0.40	4.83	0.35
P	0.6457	0.1150	0.5284	0.0340	0.5511
A-2	0.29	0.58	0.3	0.7	10.4
B-2	0.37	0.60	0.4	1.0	12.7
Difference	−0.08	−0.02	−0.1	−0.3	−2.3
EMS	0.00303	0.01129	0.00625	0.05525	13.85268
F	8.39	0.06	6.57	4.41	1.38
P	0.0062	0.8125	0.0143	0.0422	0.2474
A-3	0.28	0.52	0.3	0.5	8.9
B-3	0.35	0.52	0.3	0.8	10.6
Difference	−0.07	0	0	−0.3	−1.7
EMS	0.00303	0.1129	0.00625	0.05525	13.85268
F	7.10	0.00	0.69	8.59	0.84
P	0.0112	0.9527	0.4122	0.0056	0.3650
[(A-1) + (A-2) + (A-3)]/3	0.30	0.58	0.3	0.6	9.7
[(B-1) + (B-2) + (B-3)]/3	0.35	0.56	0.3	0.9	11.5
Difference	−0.05	0.02	0	−0.3	1.8
EMS	0.00303	0.01129	0.00625	0.00525	13.85268
F	12.09	0.58	5.41	17.42	2.40
P	0.013	0.4528	0.0253	0.0002	0.1294
[(A-1) + (A-2) + (A-3) + (B-1) + (B-2) + (B-3)]/6	0.33	0.55	0.3	0.8	10.6
C	0.20	0.47	0.4	0.4	11.0
Difference	0.13	0.08	−0.1	0.4	−0.4
EMS	0.00303	0.01129	0.00625	0.05525	13.85268
F	31.17	6.41	0.85	12.66	0.19
P	0.0001	0.0155	0.3623	0.0010	0.6659

NOTE: For explanation of thinning treatments and definitions of abbreviations see Table 1. Degrees of freedom were as follows: total = 54; error = 39; model = 15 (block = 2; treatments = 6; growth periods = 1; treatments × growth period interaction = 6).

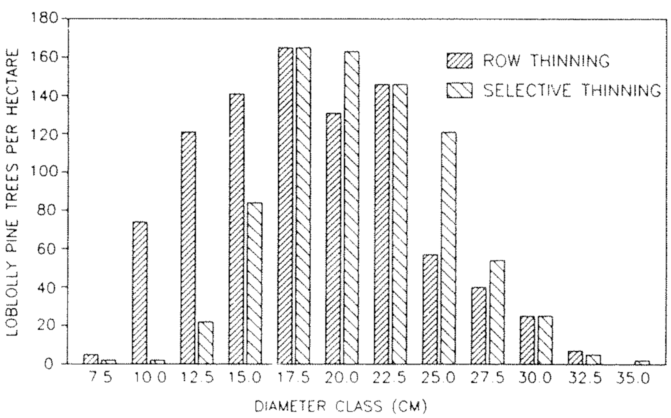

FIG. 1. Comparison of the average distribution of diameters (centimetres at breast height) by 2.5-cm classes for row-thinned and selectively thinned loblolly pine, following 10 years of growth after the initial thinning treatments were applied.

Diameter increment of the 125 largest trees per hectare was also used to compare treatment effects on the "crop" trees in the plantations. In this comparison the growth advantage, when averaged over all treatments, was minimal in row-thinned stands of loblolly pine (0.02 cm/tree per year, 4% difference, $P = 0.4528$) and zero in slash pine stands.

Net periodic basal-area growth was clearly better in selectively thinned stands of both species (Tables 5 and 6). The mean difference in periodic basal-area growth between thinning treatments was 0.3 $m^2 \cdot ha^{-1} \cdot year^{-1}$ in loblolly pine plantations (a 50% advantage in selectively thinned stands, $P = 0.0002$); the difference was 0.4 $m^2 \cdot ha^{-1} \cdot year^{-1}$ in slash pine plantations (an 80% advantage of selective thinning over row thinning, $P = 0.0001$).

Net periodic cubic metre volume growth (inside bark) in selectively thinned loblolly pine stands was 19% ($P = 0.1294$) better than in row-thinned stands; the average difference in growth was 1.8 $m^3 \cdot ha^{-1} \cdot year^{-1}$ (Table 5). These values were similar, but higher, for slash pine (Table 6); the average advantage was 4.3 $m^3 \cdot ha^{-1} \cdot year^{-1}$, which represented 50% more growth.

For both species, row thinning appeared to accelerate

TABLE 6. Comparison of average annual growth responses over two 5-year measurement periods for planted slash pine following row thinning or selective thinning

Thinning treatment	Diameter increment, all trees (cm·yr^{-1})	Diameter increment, 125 largest trees (cm·yr^{-1})	Dominant–codominant ht. growth (m·yr^{-1})	Net basal-area growth (m^2·ha^{-1}·yr^{-1})	Net total inside-bark vol. growth (m^3·ha^{-1}·yr^{-1})
A-1	0.56	0.87	0.5	0.3	6.9
B-1	0.63	0.80	0.6	1.0	13.3
Difference	−0.07	0.07	−1.0	−0.7	−6.4
EMS	0.00342	0.00594	0.00749	0.14372	8.12273
F	6.33	4.58	3.17	15.21	25.18
P	0.0149	0.0369	0.0807	0.0003	0.0001
A-2	0.40	0.64	0.5	0.5	9.5
B-2	0.45	0.68	0.6	0.9	13.2
Difference	−0.05	−0.04	−0.1	−0.4	−3.7
EMS	0.00342	0.00594	0.00749	0.14372	8.12273
F	3.74	0.92	0.24	5.18	8.53
P	0.0582	0.3418	0.6272	0.0269	0.0051
A-3	0.44	0.70	0.5	0.6	9.3
B-3	0.55	0.75	0.5	0.8	12.0
Difference	−0.11	−0.05	0	−0.2	−2.7
EMS	0.00342	0.00594	0.00749	0.14372	8.12273
F	15.74	1.97	0.04	1.91	4.33
P	0.0002	0.1667	0.8508	0.1729	0.0422
[(A-1)+(A-2) +(A-3)]/3	0.47	0.74	0.5	0.5	8.6
[(B-1)+(B-2) +(B-3)]/3	0.54	0.74	0.6	0.9	12.9
Difference	−0.07	0	−0.1	−0.4	−4.3
EMS	0.00342	0.00594	0.00749	0.14372	8.12273
F	23.62	0.02	1.44	19.04	33.47
P	0.0001	0.8988	0.2351	0.0001	0.0001
[(A-1)+(A-2)+(A-3) +(B-1)+(B-2) +(B-3)]/6	0.50	0.74	0.5	0.7	10.7
C	0.32	0.60	0.5	0.4	12.5
Difference	0.18	0.14	0	0.3	−1.8
EMS	0.00342	0.00594	0.00749	0.14372	8.12273
F	89.07	28.06	0.95	6.86	3.26
P	0.0001	0.0001	0.3332	0.0114	0.766

NOTE: For explanation of thinning treatments and definitions of abbreviations see Table 1. Degrees of freedom were as follows: total = 69; error = 54; model = 15 (block = 2; treatments = 6; growth periods = 1; treatments × growth period interaction = 6).

mortality faster than selective thinning (Tables 7 and 8). In all cases significantly more trees died in row-thinned plots than in selectively thinned plots. On average, volume and basal-area losses due to mortality were much greater in row-thinned plots as well. The mean treatment differences between row and selective thinnings for the various categories of mortality are summarized below. The probabilities of statistical significance for these differences are less than 0.01.

	Loblolly pine		Slash pine	
	Mean difference	Mean % difference	Mean difference	Mean % difference
Trees died (no./ha per yr)	20	333	20	167
Basal area lost (m^2·ha^{-1}·yr^{-1})	0.2	200	0.2	66
Volume lost (m^3·ha^{-1}·yr^{-1})	1.0	167	1.6	94

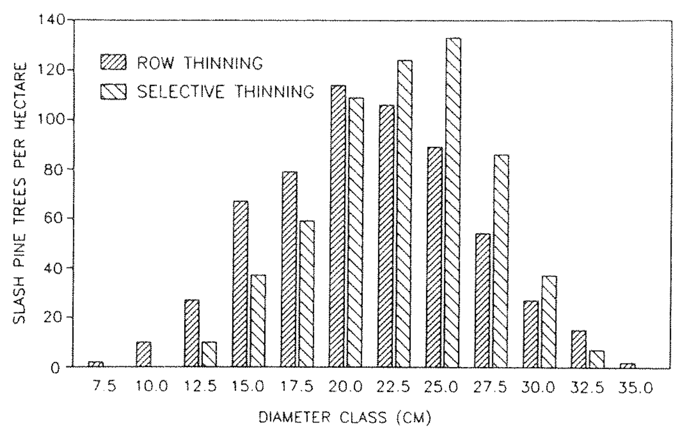

FIG. 2. Comparison of the average distribution of diameters (centimetres at breast height) by 2.5-cm classes for row-thinned and selectively thinned slash pine, following 10 years of growth after initial thinning treatments were applied.

Plot records indicated that row-thinned plots were more susceptible to losses from wind, ice, and fusiform rust canker

TABLE 7. Comparison of average annual mortality responses over two 5-year measurement periods for planted loblolly pine following row thinning or selective thinning

Thinning treatment	No. of trees died/ha per year	Basal area ($m^2 \cdot ha^{-1} \cdot yr^{-1}$)	Inside-bark vol. ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)
A-1	23	0.3	1.5
B-1	5	0.1	0.4
Difference	18	0.2	1.1
EMS	80.17690	0.01901	0.84020
F	16.34	8.01	5.49
P	0.0002	0.0073	0.0243
A-2	25	0.3	1.5
B-2	7	0.1	0.9
Difference	18	0.2	0.6
EMS	80.17690	0.01901	0.08420
F	16.46	2.77	1.88
P	0.0002	0.1039	0.1785
A-3	30	0.3	1.8
B-3	7	0.1	0.5
Difference	23	0.2	1.3
EMS	80.17690	0.01901	0.84020
F	28.07	12.82	7.49
P	0.0001	0.0009	0.0093
[(A-1) + (A-2) + (A-3)]/3	26	0.3	1.6
[(B-1) + (B-2) + (B-3)]/3	6	0.1	0.6
Difference	20	0.2	1.0
EMS	80.17690	0.01901	0.84020
F	59.83	21.75	13.87
P	0.0001	0.0001	0.0006
[(A-1) + (A-2) + (A-3) + (B-1) + (B-2) + (B-3)]/6	16	0.2	1.1
C	60	0.6	3.1
Difference	−44	−0.4	−2.0
EMS	80.17690	0.01901	0.84020
F	133.58	40.11	29.16
P	0.0001	0.0001	0.0001

NOTE: For explanation of thinning treatments and definitions of abbreviations see Table 1. Degrees of freedom were as follows: total = 54; error = 39; model = 15 (block = 2; treatments = 6; growth periods = 1; treatments × growth period interaction = 6).

than those on selectively thinned plots for the first 5 years. Also, slash pine appears to be more susceptible to these causes of mortality than loblolly pine. After the first 5 years these three factors caused 71% of the mortality in slash pine plots and 32% in the loblolly pine plots. The same relationships may persist; however, causes of mortality were not noted or estimated during the second 5-year period. Loblolly and slash pine mortality from all causes was usually significantly less during the second 5-year period than during the first 5-year period. However, for slash pine, mortality in the control plots was greater during the second 5-year period.

As shown earlier with the comparison of quadratic mean dbh values, more large-diameter trees occurred in selectively thinned stands than in row-thinned stands. This shifted the diameter distribution frequency curves of the selectively thinned stands to the right of the comparable curves for the row-thinned stands. Frequency graphs of the thinned stand diameter distributions at the end of the growth period show that for both species the row-thinned stands' distribution curve was approximately symmetrical in shape. However, for selective thinning, the curve was somewhat skewed to the right for loblolly pine and skewed to the left for slash pine (Figs. 1 and 2).

Discussion and conclusions

This study provides evidence to indicate that in plantations similar to those in this experiment, growth and yield of planted loblolly and slash pines will be higher in stands thinned selectively from below than in stands row thinned to a comparable basal area per unit area. The results hold, with only one exception, for diameter, basal area, and volume in all three of the row-thinning and selective thinning treatments applied. In some cases the growth or yield differences are small and might be attributable to chance variation. The authors have presented sufficient statistical data for readers to determine the significance of each difference in light of their own situation. Each type of growth and yield measure can be summarized as follows.

Diameter increment differences resulting from either row thinning or selective thinning followed the same pattern,

TABLE 8. Comparison of average annual mortality responses over two 5-year measurement periods for planted slash pine following row or selective thinning

Thinning treatment	No. of trees died/ha per year	Basal area ($m^2 \cdot ha^{-1} \cdot yr^{-1}$)	Inside-bark vol. ($m^3 \cdot ha^{-1} \cdot yr^{-1}$)
A-1	35	0.6	3.9
B-1	10	0.2	1.4
Difference	25	0.4	2.5
EMS	194.677	0.08452	4.17107
F	16.06	9.66	7.11
P	0.0002	0.0030	0.0101
A-2	32	0.6	3.6
B-2	14	0.3	1.8
Difference	18	0.3	1.8
EMS	194.677	0.08452	4.17107
F	8.27	3.24	3.72
P	0.0058	0.0773	0.592
A-3	29	0.5	2.4
B-3	13	0.3	2.2
Difference	16	0.2	0.2
EMS	194.677	0.08452	4.17107
F	6.42	1.12	0.03
P	0.0142	0.2941	0.8620
[(A-1) + (A-2) + (A-3)]/3	32	0.5	3.3
[(B-1) + (B-2) + (B-3)]/3	12	0.3	1.7
Difference	20	0.2	1.6
EMS	194.677	0.08452	4.17107
F	29.56	11.88	7.58
P	0.0001	0.0001	0.0080
[(A-1) + (A-2) + (A-3) + (B-1) + (B-2) + (B-3)]/6	22	0.4	2.5
C	59	0.9	5.5
Difference	−37	−0.5	−3.0
EMS	194.677	0.08452	4.17107
F	59.60	23.05	17.48
P	0.0001	0.0001	0.0001

NOTE: For explanation of thinning treatments and definitions of abbreviations see Table 1. Degrees of freedom were as follows: total = 69; error = 54; model = 15 (block = 2; treatments = 6; growth periods = 1; treatments × growth period interaction = 6).

regardless of species. Residual trees (all, or the largest "crop" trees) in row-thinned stands generally grew less in diameter than those in selectively thinned stands, though the differences were not large. This has been the pattern in similar studies with other species, too. For example, Elfving (1985) reported that in spruce and pine plantations in Sweden the advantage in diameter increment of selective thinning over row thinning was only 4–6%. So from the standpoint of mean increment alone, not much is lost with row thinning.

The one exception to this pattern occurred in the "remove every other row" treatment. The PAI of the crop trees was greater in row-thinned stands than in selectively thinned stands for both species. Removal of every other row always ensured that all remaining trees were free of light competition on two sides. Furthermore, if we assume that approximately equal numbers of dominant, codominant, intermediate, and suppressed trees were left after the row-thinning operation, then there was a good chance that a leave dominant or codominant tree was also taller than at least one of its neighbors within the row. On the other hand, the selective thinnings were not done strictly from below and there might have been some clumping of the dominants and codominants. Therefore, the resulting increment advantage for the row-thinned crop trees is quite possible and reasonable when every other row is thinned.

Growth and yield on the basis of net basal area per unit area were significantly higher in selectively thinned stands than in row-thinned stands, and the yield was from fewer, larger trees. Part of this advantage was due to the greater diameter increment in selectively thinned stands and the fact that, given an equal diameter increment rate, basal-area increment is greater on larger-diameter trees. However, mortality, which averaged three times higher in row-thinned stands than in selectively thinned stands, was also an important factor. Because of the types of thinning, more trees remained per unit area after thinning in the row-thinned stands than in the selectively thinned stands. However, 10 years later there were slightly fewer trees per unit area in row-thinned slash pine stands

Heretofore, the significance of the volume and basal-area losses due to increased mortality in row-thinned stands has only been strongly emphasized in those studies that reported the high susceptibility of row-thinned residual trees to wind and ice damage (Belanger and Brender 1968; Shepard 1975, 1978). In the West Gulf region this is definitely a factor (Williston 1974; Enghardt 1969; Anonymous 1971), and ice damage was a source of mortality in this experiment, particularly for the slash pine.

The results showed that volume growth and yield were also better in selectively thinned stands than in row-thinned stands, but the differences were not as strong in loblolly pine stands as in slash pine stands. A confounding factor in the case of volume differences might have been a possible site advantage for selectively thinned stands of both species. The results showed that mean heights of dominant and codominant trees were higher in these stands. This height advantage might have resulted from higher site quality, but it might also have been caused by the cutting of proportionately more dominants from row-thinned stands than from selectively thinned stands. The latter process would tend to lower the mean height of the dominants and codominants in row-thinned stands.

Therefore, the results of this study are in agreement with those of the other studies reviewed, and show that there will likely be less diameter increment and less net basal area and cubic metre volume per unit area growth and yield, and the growth will be on smaller-sized trees, if row thinning is used in place of selective thinning from below. The net basal-area growth differences were the most notable; these were mainly caused by greater mortality and lower mean diameter growth of the residual trees in the row-thinned stands. Of the two species tested, growth and yield differences were greater in slash pine than in loblolly pine plantations. The authors believe these relationships will also hold true for these species planted at other locations, and for other species and other geographic areas.

Finally, it should be pointed out that the main advantages of row thinning over selective thinning are lower thinning costs and easier stand access for further thinnings or other stand treatments. This study was not designed to answer the question of which method may be the best, based on economic considerations. However, the results clearly show that the lower costs of thinning by rows or swaths should be weighed against the reduced plantation growth and yield, and hence probable lower stand value at final harvest, that will result from application of this procedure.

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