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Loblolly pine cutting morphological traits: Effects on rooting and field performance

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Abstract. Shoot cuttings were harvested from four-year-old, loblolly pine hedges in March and September of 1987, and placed into a series of factorial combinations of cutting length, diameter class, and the presence/absence of a terminal bud to assess effects on rooting and field performance. Average rooting in the March trial was 50 percent and only 20 percent for the September trial; however, the best treatment in March yielded 100 percent rooting. Terminal bud status did not appear to influence percent rooting. Shorter cuttings (5.1 or 7.6 cm) with an average diameter of 2 or 3 mm tended to root better and develop more roots. Field performance of the rooted cuttings through age five suggests that the original cutting does not require a terminal bud, but the best set of morphological traits differ depending on bud status. Considering both rooting ability and field growth with an original tip bud present, the best cutting dimensions were 5.1 or 7.6 cm long and 2 or 3 mm in diameter. Without a tip bud present, cutting dimensions were restricted to 7.6 or 10.2 cm long and 3 mm in diameter. Number of main roots was a weak predictor of tree height or dbh at age five.

Introduction

Mass propagation of outstanding full-sib families, or select genotypes within those families, for plantation establishment has the potential to strongly impact productivity of commercial forests in the southeastern United States. Experimental results with loblolly pine (*Pinus taeda* L.) have indicated that high shoot multiplication rates can be achieved through the management of hedged stock plants (Foster and Shaw 1987). Even so, it is widely recognized that loblolly pine is difficult to root relative to other tree species (Wise and Caldwell 1994). The capacity of cuttings to root is influenced by many factors, including cutting genotype, pre- and post-treatment of the cuttings, and the rooting environment (Hartmann and Kester 1983).

Many published articles describe the effects of genotype, cutting physiology, exogenous hormone treatment, and environment on the rooting of loblolly pine and slash pine (*Pinus elliottii* Engelm.) cuttings (Bower and van Buijtenen 1977; Foster 1990; Greenwood et al. 1980; Hare 1974). In contrast, few data are available regarding the relationship between the morphological features of the cuttings and their rooting. Even less is known regarding the relationship between morphological traits and growth of rooted cuttings upon outplanting. One such study with loblolly pine was conducted by Goldfarb et al. (1988) in which they investigated the relationship between adventitious root system attributes and subsequent height growth of rooted cuttings. The relationship was weak but significant through the nursery phase but disappeared after one growing season in the field. This type of information will be crucial for developing rooted cutting grading rules similar to those developed by Wakeley (1954) for pine seedlings.

In other tree species, conflicting results exist regarding the effects of cutting length on rooting. Fielding (1954) found that shorter cuttings of radiata pine (*Pinus radiata* D. Don) tended to give higher rooting percentages. This tendency mainly was influenced by the poor rooting of the longest cutting length treatment (25.4 cm). In Fraser fir (*Abies fraseri* [Pursh] Poir), cutting length did not affect percentage of rooting (Miller et al. 1982). However, in sequential, single-node cuttings of the West African hardwood 'Obeche' (*Triplochiton scleroxylon* K. Schum), Leakey and Mohammed (1985) discovered that percentage rooting and number of roots per rooted cutting were positively correlated to cutting length.

The effect of cutting diameter also appears to be species specific. In rooted cutting trials of *P. radiata*, Fielding (1969) concluded that shoot caliper had little effect on rooting percentages, but there was a strong positive relationship between cutting diameter and subsequent growth of rooted cuttings transplanted to nursery beds. Howard and Ridout (1991a) showed that as the diameter of plum (*Prunus insititia* 'Pixy') cuttings increased from 4 to 12 mm, percentage rooting decreased. Although Ritchie et al. (1993) did not take measurements on Douglas-fir *(Pseudotsuga menziesii* [Mirb] Franco) cuttings when set, they did observe a clear survival and height growth gradient in proportion to stem diameter of the rooted cutting. Plants having larger diameters had higher percentage survival and better growth than those with smaller diameter. In field plantings of hybrid poplar rooted cuttings (*Populus* cv. 'Betulifolia' *x P. trichocarpa* Torr. & Gray, *F! nigra* L. x *P. laurifolia* Ledeb., *P. tristis* Fisch. *x P. balsmifera*, *P.* cv. 'rasumowskyana' x *P*. cv. 'incrassata', and *P. deltoides* Bartr. x *P.* cv. 'caudina'), Dickman et al. (1980) demonstrated that large-diameter cuttings survived better and produced taller shoots than small diameter cuttings. In hybrid tropical pine (*Pinus caribea* var. hondurensis x *P. tecunumanii*), cuttings having a diameter of at least 2 mm rooted better than thinner cutting stock (Haines et al. 1992). Diameter:length ratios in plum cuttings have shown that a smaller ratio (thinner, longer shoots) was accompanied by improved rooting (Howard and Ridout 1991b).

In similar fashion, the effect of the presence or absence of a terminal bud on the rooting of cuttings and their subsequent growth varies by tree species. Havmoller (1981) determined that the presence or absence of a terminal bud on Norway spruce (*Picea abies* [L.] Karst.) cuttings had no effect on percent rooting, root number, or length of the longest root. In contrast, Haissig (1982) found markedly reduced rooting of jack pine (*Pinus banksiana* Lamb.) cuttings when the terminal portion of the cutting (including the tip bud) and needles were removed.

The current study explored the relationship between various morphological traits of loblolly pine cuttings and their ability to root, as well as subsequent growth upon outplanting. The objectives of this study were to determine the effects of (1) cutting length, (2) cutting diameter, and (3) the absence/presence of a terminal bud of loblolly pine cuttings on their rooting success, and field performance following outplanting.

Materials and methods

Rooting trials

Shoot cuttings were harvested from four-year-old, loblolly pine hedges maintained by International Forest Company near Birmingham, Alabama. The donor hedges represented a large number of genotypes across many families. A broad genetic base of trees was sampled so that inferences would apply to the entire population rather than specific families. Cuttings were collected from the same population of genotypes in March and September 1987. For each harvest date, the cuttings came from the distal end of fully-expanded shoots of each hedge plant. The shoot diameter classes were chosen to cover the three diameters that typically develop for loblolly pine shoots on hedged trees that are 0.50 m tall.

Cuttings were arranged into factorial combinations of three morphological categories: cutting length – 5.1, 7.6, 10.2, and 12.7 cm (2, 3, 4, and 5 in, respectively); cutting diameter class – small (2 mm), medium (3 mm), and large (7 mm); and terminal bud – absent (0) and present (1). In order to expedite the process of setting the cuttings, the basal diameter of each cutting was not measured. Instead, cuttings were placed into the three diameter classes based upon visual inspection, choosing cuttings with a uniform diameter within each class. Then, after the cuttings were set, a sample of 30 cuttings was measured in each class in order to estimate the mean diameter for each class. The range of diameters within each class was quite narrow. Although the 2 mm and 3 mm diameter class cuttings appear to the reader to be extremely close in size, in reality the 3 mm cuttings were 50% larger in diameter and quite distinct. Most of the cuttings produced on the hedges fell in the 3 mm diameter class.

The small- and medium-diameter cuttings came from hedges that originated from full-sib families created by sets of factorial crosses among 127 trees that were chosen from a pool of tested, first-generation selections from a combination of the North Carolina State University (NCSU) - Industry Cooperative Tree Improvement Program and the Cooperative Program between the USDA Forest Service and the Georgia Forestry Commission (Foster 1990). The large-diameter material came from hedges that originated from full-sib families among first-generation selections from Weyerhaeuser Company's breeding program. The selections from Weyerhaeuser Company were a subset of the trees in the NCSU program. Parental selection for both hedge groups was based on resistance to the fusiform rust fungus (*Cronartium quercuum* [Berk.] Miyabe ex Shirai f.sp. *fusiforme*) as well as superior height growth as evidenced by progeny test results. No selection pressure had been applied for rooting ability.

The larger cutting caliper (7 mm) was made possible by collecting the material from hedges that had not been sheared as recently as the other hedges. The NCSU and USDA parental source hedges were sheared three times per year, twice in the growing season and once in the dormant season. The Weyerhaeuser parental source hedges, however, had not received the second growing season shearing during the previous summer, otherwise the shearing times were the same.

After collection, the basal 1 cm of each cutting was moistened with water and then dipped into a modified Hare's rooting powder (Hughes 1987). The treated cuttings were set into 93 cm^3 plastic containers with a 2:1 (v:v) mixture of peat:perlite and the racks of set cuttings were placed in an air-conditioned and heated greenhouse with intermittent fogging and misting (Hughes 1987; Foster 1990). Relative humidity was maintained between 95 and 100 percent and with a stable temperature of 24 °C during both rooting seasons.

Treatment plots were arrayed in a completely randomized fashion in each of the two rooting trials. Each plot consisted of a row of five cuttings per treatment, and each treatment was replicated four times per trial. Hence, each rooting trial contained 480 cuttings (24 treatments x 4 replications x 5 cutting plots).

After four months in the rooting environment, the cuttings were assessed for rooting. A cutting with one or more roots in excess of 1 mm in length (i.e., a root primordium was evident) was regarded as being rooted. The authors have successfully used this definition of rooting for several species of trees over the years with success, as did Goldfarb et al. (1998) with loblolly pine. With proper hardening off, a high percentage of rooted cuttings develop a good root system and survive. Rooting success was expressed as a percentage of the cuttings that rooted in each plot. In addition to rooting success, the number of roots and the number of shoots that elongated during the rooting period were recorded for each successfully rooted cutting. Upon completion of data collection, the rooted cuttings were transplanted to 150 cm^3 pots. They were kept in the greenhouse for an additional hardening-off period (about 2-3 weeks) with increasingly less frequent watering until a normal watering regime for seedlings was reached, then they were moved mto an outdoor shadehouse until outplanting.

Field trial

In December 1987, the rooted cuttings were planted on an old field site at International Forest Company headquarters near Birmingham, Alabama. Tree spacing was 1.2 x 1.5 m. Because rooting in the September trial was poor, only rooted cuttings from the March trial were outplanted. The planting design was completely randomized, with 1 to 10 trees per treatment (average was 7 trees per treatment for a total of 166 trees) planted as single-tree plots. A border row of seedlings surrounded the study.

The following traits were measured: total height (nearest 0.03 m) at time of planting, and annually through age 5, and stem diameter (nearest 0.25 cm) at breast height (dbh) at age 3, 4, and 5.

Data analysis

Before conducting the analysis of variance, the data were checked to determine whether the model assumptions (e.g., normally distributed errors and homogeneity of variances) were fulfilled (Sokal and Rohlf 1987). Because the rooting percentage data are based upon a binomial response and some mean rooting percentages lie outside the stable variance range of 30 to 70 percent, all rooting percentage data were transformed to $\arcsin \sqrt{\bar{p}}$, where p is the rooting percentage (Anderson and McLean 1974). All other analyses were performed on untransformed data.

Table 1. Analysis of variance for the morphological traits of cutting length (LTH), cutting diameter (DIA), and presence or absence of the terminal bud (BUD) on rooting percentage, number of roots, and number of shoots for cuttings set in March, 1987, taken from four-year-old loblolly pine donor plants.

	Rooting percentage			Number of roots			Number of shoots		
Source	df	MS	P-value	df	MS	P-value	df	MS	P-value
LTH	3	1405.67	0.0001	3	16.18	0.0313	3	7.97	0.0041
BUD	1	95.99	0.4183	1	11.79	0.1396	1	32.74	0.0001
LTH*BUD	3	698.33	0.0045	3	9.00	0.1730	3	0.41	0.8690
DIA	2	743.00	0.0087	2	13.51	0.0832	2	20.22	0.0568
LTH*DIA	6	1913.83	0.0001	6	4.51	0.5389	6	1.23	0.6403
BUD*DIA	2	31.83	0.8029	2	0.72	0.8739	2	1.08	0.5378
LTH*BUD*DIA	6	596.17	0.0016	6	2.91	0.7650	6	1.72	0.4326
Plot (LTH*BUD*DIA)		NA	NA	59	7.03	0.0928	59	1.76	0.4551
Error	72	1081.57		160	5.35		160	2.48	
R-Square		0.74			0.49			0.42	

Analysis of variance (ANOVA) procedures were used to test for significant effects of the cutting morphological traits for the response variables measured (Table 1). All effects were considered to be fixed. To compensate for unbalanced data, Type III sums of squares were used for the F-tests (SAS Institute Inc. 1994). Regression procedures were used to evaluate the number of roots as a predictor of the cutting's field performance (SAS Institute Inc. 1994). A probability level of 0.05 or less was judged significant in all statistical tests.

Results and discussion

Rooting trials

The average rooting (across all 24 treatments) observed in the March trial was 50 percent; however, rooting dropped to 20 percent for the September trial. In March, the best treatment for rooting yielded 100 percent (Table 2). These results contrast with those of Reines and Bamping (1960) for loblolly pine in which rooting percentage for both March and September were only about 10 percent. Seasonal rooting percentages for their entire study tended to be quite low and may have been influenced by generally poor rooting protocols. Bower and van Buijtenen (1977) however, observed seasonal patterns in their rooting of four-year-old slash pine cuttings that were similar to our results. With loblolly pine, Foster (1990) reported an overall rooting of 43 percent

2. Mean rooting percentages based on terminal bud status, cutting length, and cutting diameter for cuttings set in March, 1987, taken from four-year-old loblolly pine donor plants.

Terminal bud status	Cutting length (cm)	Cutting diameter class (mm) 2	3	7	Mean
Absent	5.1	30	80	60	57
	7.6	60	70	75	68
	10.2	100	60	20	60
	12.7	20	20	5	15
	Mean	53	57	40	50
Present	5.1	70	100	30	67
	7.6	75	75	35	62
	10.2	75	20	30	42
	12.7	20	35	50	35
	Mean	60	57	36	50

with February, June, and July setting dates, and Goldfarb et al. (1998) found 44 percent overall rooting when setting cuttings in February. In the current study, the poorer rooting success in September could be due to a number of factors, most notably maturation, photoperiod, and carbohydrate reserves in the donor plant. The greenhouse was air-conditioned, and environments were similar during both rooting periods.

Donor plant maturation leads to a general reduction in rooting ability (Foster et al. 1981; Marino 1982). The threshold age at which this decrease occurs and the rate of decline may vary among species and even among clones within a species. In his work with southern pines, Marino (1982) noted an initial threshold decline at three years of age. The donor plants in the current study were repeatedly hedged, as described by Libby et al. (1972) for radiata pine, to a maximum height of 0.5 m presumably retarding the aging process. The March cuttings were from dormant material that had developed on the donor plants the previous growing season when the plants were 3-years-old. The September cuttings developed on the donor plants that were 4-years-old from seed. Even though the hedges span this maturation threshold, the heterogeneous genetic mixture of the cuttings makes it unlikely that the dramatic decline in rooting from March to September was due to maturation alone, especially given the intensive shearing regime.

More plausibly, the decline may have been due to changes in photoperiod and subsequent vernalization. With the onset of bud dormancy in late summer, loblolly pine cuttings collected in September are entering a phase of greatly reduced metabolic activity. Roberts and Fuchigami (1973) found that Douglas-fir cuttings rooted poorly in September and October when bud dormancy was most pronounced. Cold treatment in October and November enhanced rooting and removed bud dormancy. The loblolly pine cuttings taken in March had been exposed to a full vernalization period and were ready to resume full metabolic activity, as well as adventitious root formation.

Because of the poor rooting success in September, the discussion of results in the rest of the manuscript will focus on the March rooting data. Regarding rooting percentages, analysis of variance revealed a significant, three-way interaction among cutting length, cutting diameter, and presence/absence of the cutting's terminal bud (Table 1). The three-way interaction precluded means separation based on any of the main effects; but a few general observations can be made based on results (Table 2). First, there is no general difference in percentage rooting between cuttings having a terminal bud and those without (Table 2). Both classes exhibited overall rooting of 50 percent. Second, shorter cuttings averaging 2 or 3 mm in diameter generally have higher rooting percentages. Third, either 5.1 or 7.6 cm long cuttings gave the best rooting. Fourth, cuttings should be avoided that are 5.1 cm long, 2 mm in caliper, and with no tip bud. With loblolly pine, Goldfarb et al. (1998) used cuttings that were 9 cm long. They did not give the diameter but all cuttings had tip buds (personal communication, Barry Goldfarb, North Carolina State University, Raleigh, NC). Their overall rooting of 44 percent compares well with our results for 10.2 cm cuttings with a tip bud (Table 2).

Cutting length had a significant effect on both the number of roots as well as the number of shoots formed (Table 1). A Student-Newman-Keuls mean separation analysis revealed that the 2.5 roots produced by those cuttings in the 12.7 cm length class were significantly less than the 3.5, 3.7, and 4.2 roots produced by the 10.2, 7.6, and 5.1 cm-long cuttings, respectively. The 5.1 cm-long cuttings produced 1.6 shoots per cutting. This was significantly different than the 2.2 shoots produced on 7.6 cm-long cuttings, but not different from the 2.1 or 2.0 shoots produced on the 12.7 or 10.2 cm-long cuttings, respectively. The ultimate value of this difference appears minor since multiple tops (e.g., forking) in the field were very rare for any treatment after five years.

No discernible patterns were evident from efforts to quantify the effect of cutting length and diameter on rooting by calculating diameter:length ratios similar to those developed by Howard and Ridout (1991a). This lack of pattern was probably due to the fact that a diameter-class average was used instead of measuring the diameter of the individual cuttings at the time they were set. It is strongly recommended that future rooting morphological studies collect such data.

It is generally accepted that severe hedging results in long, vigorous, adventitious or auxiliary shoots that exhibit enhanced rooting (Garner and Hatcher 1964; Howard et al. 1985, 1989a, 1989b). In the current study, the highest rooting treatments varied somewhat depending on the presence of a tip bud on the cuttings (Table 2) although the overall average rooting percentage between presence or absence of the tip bud was the same (both with 50%). The 12.7 cm long cuttings tended to root worse than the other 3 cutting lengths (Table 2). With a tip bud, 2 and 3 mm diameter cuttings rooted better than 7 mm for 5.1 and 7.6 cm long cuttings (Table 2). Without a tip bud, the 7 mm diameter cuttings rooted about as well as the 2 or 3 mm cuttings for 7.6 cm long cuttings, and 7 mm diameter cuttings rooted better than the 2 mm diameter cuttings for 5.1 cm long cuttings. Howard and Ridout (1991a, 1991b) noted that thinner plum cuttings were produced on shoots which arose in sub-dominant positions on the framework of the stock plant nearest to the root system, and they grew more slowly and stopped growing before shoots in the more dominant crown positions. These thinner, shorter cuttings tended to root more readily than those cuttings prepared from larger shoots which is similar to the situation in the current study with loblolly cuttings with a tip bud present.

Howard and Ridout (1991a) argue that high shoot vigor and high rooting are not causally linked, and that both may be responses to a pruning-related process not yet understood. These results are relevant to understanding the concept of rejuvenation. They suggest that such enhanced rooting is not a direct consequence of vigorous shoot growth and may reflect more the fact that severe hedging is confounded because regenerated shoots arise only in the lower portions of the hedge close to the root system. Further research is needed to evaluate the relationship between where the pine cutting is collected within the hedge and its ability to root.

Finally, the presence or absence of a terminal bud had a significant effect on the number of shoots (terminal shoots in appearance) that developed on the rooted cutting. If the cutting had a terminal bud, then 1.5 shoots were produced on average. However, when no terminal bud was present, the average rose to 2.3 shoots. As reported earlier and in the following section, the increased number of shoots during the rooting phase did not result in an increased number of forked trees in the field after five years. In all cases, a single dominant leader developed in the trees in the field.

Field trial

Probability values (P-values) obtained from the analysis of variance of the full model for all of the response variables measured are given in Table 3. For tree height growth, there were significant length x bud and diameter x

3. Probability (P) values obtained from the analysis of variance for the morphological traits of cutting length (LTH), cutting diameter (DIA), and presence or absence of the terminal bud (BUD) on resulting height and diameter growth at age 5 of loblolly pine rooted cuttings that were outplanted in January, 1988.

		Height					Diameter		
Source	df	Age1	Age2	Age3	Age4	Age5	Age3	Age4	Age5
LTH	3	0.0002	0.0004	0.0013	0.0005	0.0053	0.0001	0.0006	0.0012
BUD	1	0.6296	0.0812	0.1704	0.0955	0.1212	0.0373	0.2827	0.2423
LTH*BUD	3	0.1023	0.0146	0.0033	0.0062	0.0006	0.0006	0.0067	0.0057
DIA	2	0.3279	0.5631	0.5862	0.3311	0.1706	0.4812	0.8945	0.4303
LTH*DIA	6	0.0001	0.0123	0.2284	0.2011	0.1465	0.0009	0.1533	0.0507
BUD*DIA	2	0.0502	0.0288	0.0241	0.0187	0.0061	0.0103	0.0023	0.0010
LTH*BUD*DIA	6	0.4484	0.1300	0.1936	0.1046	0.1075	0.0276	0.1750	0.1765
R-Square		0.35	0.25	0.22	0.23	0.27	0.34	0.25	0.26

Table 4. Probability (P) values obtained from analyses of variance for the physical traits of cutting length (LTH) and cutting diameter (DIA), by the presence or absence of the terminal bud, on resulting height and diameter growth at age 5 of loblolly pine rooted cuttings that were outplanted in January, 1988.

		Height					Diameter		
Source	df	Age1	Age2	Age3	Age4	Age5	Age3	Age4	Age5
Terminal bud absent									
LTH	3	0.1475	0.0751	0.6527	0.7666	0.1684	0.0052	0.0470	0.0758
DIA	2	0.0139	0.0441	0.0665	0.0675	0.0240	0.0075	0.0129	0.0071
LTH*DIA	6	0.0151	0.0988	0.6549	0.3871	0.0553	0.0370	0.2520	0.1707
R-Square		0.33	0.26	0.15	0.17	0.28	0.33	0.26	0.27
Terminal bud present									
LTH	3	0.0005	0.0010	0.0001	0.0001	0.0005	0.0001	0.0015	0.0012
DIA	2	0.7380	0.2849	0.2180	0.1131	0.0746	0.4504	0.1209	0.0773
LTH*DIA	6	0.0091	0.1219	0.1552	0.2033	0.1790	0.0155	0.3481	0.2614
R-Square		0.35	0.25	0.29	0.28	0.25	0.34	0.24	0.24

bud interactions at ages 2 through 5. Therefore, the data were separated by terminal bud status and the appropriate two-way ANOVAs were run (Table 4). For diameter growth, virtually all two-way interactions were significant (Table 3).

With a terminal bud, cutting diameter had no significant effect on height growth (Table 4). Conversely, cutting diameter had a significant effect on the height growth of those rooted cuttings that lacked a terminal bud. In this

Table 5. Mean tree height (HT, m) and dbh (D, cm) in a field trial at ages l-5, for 3 diameter classes of loblolly pine cuttings, all of which lacked a terminal bud at setting.

Dia. class (mm)	n[a]	HT1	HT2	HT3	HT4	HT5	D3	D4	D5
2	34	0.45b	1.45b	2.80b	4.51a	5.86b	2.77b	4.90b	6.58b
3	28	0.47b	1.57ab	3.09a	4.94a	6.52a	3.33a	5.71a	7.77a
7	21	0.56a	1.68a	3.13a	4.87a	6.21ab	3.58a	5.79a	7.70a

Means separation within column by Student-Newman-Keuls procedure, 5% level.
[a] Sample size.

6. Mean tree height (HT, m) and dbh (D, cm) in a field trial at ages l-5, for 4 cutting lengths of loblolly pine cuttings, all of which possessed a terminal bud at setting.

Cutting length (cm)	n[a]	HT1	HT2	HT3	HT4	HT5	D3	D4	D5
5.1	23	0.51a	1.58a	3.15a	5.02a	6.32a	3.15a	5.54a	7.57a
7.6	29	0.52a	1.59a	3.10a	4.83a	6.31a	3.30a	5.59a	7.49a
10.2	24	0.55a	1.58a	3.09a	4.76a	6.20a	3.23a	5.74a	7.67a
12.7	7	0.36b	1.20b	2.37b	3.90b	5.25b	2.01b	4.06b	5.741,

Means separation within column by Student-Newman-Keuls procedure, 5% level.
[a] Sample size.

case, larger diameter (7 mm) cuttings had a height growth advantage in the first year (Table 5). In most subsequent years, the height of rooted cuttings with initial diameters of either 3 mm or 7 mm were not statistically different. It is noteworthy, however, that rooted cuttings with initial diameter of 3 mm were shorter in the field than those with 7 mm initial diameter in years 1 to 3; however, they overtook the 7 mm initial diameter cuttings after 4 or 5 years in the field (Table 5). Although not statistically significant yet, the advantage seems to be widening.

Cutting length was the predominating factor in determining height growth when the cuttings possessed a terminal bud, yet was non-significant when the cuttings lacked a terminal bud (Tables 4, 6, and 7). With an initial bud on the cutting, trees originating from the longest (12.7 cm) cutting length class were always shorter than the trees arising from the other three length classes (5.1, 7.6, and 10.2 cm), which gave comparable results (Table 6).

For best field growth considerations, these data suggest somewhat different initial cutting morphological traits would be desirable depending on whether the cutting had a tip bud or not. If the initial cutting had a

Table 7. Mean tree heights (HT, m) and dbh (D, cm) in a field trial at ages l-5, for 4 cutting lengths of loblolly pine cuttings, all of which lacked a terminal bud at setting.

Cutting length (cm)	n[a]	HT1	HT2	HT3	HT4	HT5	D3	D4	D5
5.1	24	0.46a	1.46a	2.96a	4.79a	5.99a	2.82a	5.03a	6.86a
7.6	26	0.49a	1.59a	3.05a	4.79a	6.29a	3.48a	5.74a	7.62a
10.2	19	0.53a	1.63a	2.91a	4.69a	6.15a	3.23a	5.46a	7.39a
12.7	14	0.45a	1.51a	2.98a	4.67a	6.29a	3.07a	5.31a	7.16a

Means separation within column by Student-Newman-Keuls procedure, 5% level.
[a] Sample size.

tip bud, any of the 3 cutting diameters (2, 3, or 7 mm) would suffice but cutting length should be 5.1, 7.6, or 10.2 cm. However, if the initial cutting did not have a tip bud, the diameter should be either 3 or 7 mm and the length could be any of the 4 tested lengths. Supporting the use of 7 mm diameter cuttings is a bit tentative due to the trend over time, compared to the 3 mm diameter cuttings, as discussed above. These general results agree with Ritchie et al. (1993) where they found that Douglas-fir cuttings of large diameter had higher survival and better growth compared to smaller-diameter cuttings. Dickman et al. (1980) observed the same response in their work with hybrid poplar.

The presence of a terminal bud might be desirable, but not necessary. Multiple shoots observed during the rooting trials yielded to a dominant leader in the field; hence, no forking. By age five, no tree in the trial had a fork. These single-stemmed individuals did not appear to be inferior in straightness to their budded counterparts (based on observation by the senior author).

Considering both rooting ability and field growth

With a difficult-to-root species like loblolly pine, propagation success rate is an important factor as is subsequent field growth in a large-scale clonal reforestation program. Some type of optimization is needed between propagation ability and subsequent growth as has been proposed by others, especially for clonal selection (Foster et al. 1985). This will entail an economic analysis to calculate the cost function for producing rooted cuttings. Tradeoffs would have to be calculated between the marginal costs of improving rooting percentage versus added product value from faster growing trees. This analysis was not done in this paper.

Our results indicate that optimal morphological traits of cuttings are less stringent when tip buds are present on the cuttings than when they are absent.

Table 8. Linear regression of mean tree height or diameter at age 5 (Y) onto the number of roots (X) from rooted cuttings having: 1) a terminal bud, 5.1 or 7.6 cm long, and a mean basal diameter of 2 or 3 mm or 2) no terminal bud, 7.6 or 10.2 cm long, and a mean basal diameter of 3 mm.

Variable	n	Regression equation	P-value	R-Square
Height, m	45	Y = 5.91 + 0.11X	0.010	0.16
Diameter, cm	45	Y = 6.66 + 0.22x	0.005	0.17

With tip buds present, rooting and field growth are best with either 5.1 or 7.6 cm long and 2 or 3 mm diameter cuttings. If tip buds are absent, rooting and field growth are best with cuttings that are 7.6 or 10.2 cm long and 3 mm in diameter.

Regressing the age five response variables (tree height or dbh) onto root number for the recommended types of cuttings yielded positive linear relationships (Table 8). For loblolly pine, Goldfarb et al. (1998) detected a correlation of 0.22 between number of roots per cutting and height of the cuttings following rooting in the greenhouse; yet the correlation disappeared after the first growing season in the field. The authors noted the possibility that transplanting the rooted cuttings may have damaged some of the root systems, especially those with a few roots. Evidence of this was expressed in relatively lower survival of rooted cuttings with a single root following transplanting to a bareroot nursery bed. In the current study, the rooted cuttings were assessed for rooting following the rooting period in the greenhouse and then carefully repotted into the 150 cm^3 containers. With this procedure, survival was essentially 100 percent. It is unknown whether this difference between the two studies influenced the relationship between rooting and subsequent growth. Although the relationship between number of roots following the rooting period and subsequent field growth is weak, it is positive (Table 8) and shifting from 1 to 5 roots yields an increase of 0.44 m (7 percent increase) and 0.88 cm (12 percent increase) in age 5 height and dbh, respectively. Clonal selection for rooting ability will improve overall rooting (Foster 1990) and perhaps enhance tree growth.

As with any plant propagation system, the goal should be a healthy, vigorous root system. Haines et al. (1992) found that the number of roots was a good predictor of height growth in the field, but less so for diameter growth. Ritchie et al. (1993) also found that within a given cutting diameter class, plants with good root systems outperformed individuals with poorer systems. Paul et al. (1993), in their western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) clonal study, found that root system volume was a significant predictor (although of little practical value due to a low R^2) of height at age 5; however, the genetic correlation between the traits was quite high.

Conclusion

Loblolly pine is a major timber species in the southeastern United States. As a result of its commercial importance, genetic improvement is vitally important. Clonal reforestation has become an alternative for many tree species and is approaching that status for loblolly pine (Foster and Shaw 1987). Large-scale rooted cutting propagation remains the crucial step in this clonal reforestation process (Foster et al. 1981).

For best combined rooting and subsequent growth, loblolly pine cuttings should meet specific standards regarding morphological traits. Cuttings either with or without a tip bud can be used. This allows second order cuttings to be collected from some longer shoots thereby increasing the number of cuttings available on each hedge. The single best cutting (with or without a tip bud) is 7.6 cm long and has a 3 mm diameter. For cuttings with tip buds, they can be either 5.1 or 7.6 cm long and either 2 or 3 mm in diameter. Without a tip bud, they can be either 7.6 or 10.2 cm long with a 3 mm diameter. More roots translate into better performance upon outplanting, but the need still exists to understand what effect root system quality plays in long-term growth and development. The extent to which the optimal morphological traits for cuttings depend on the exact propagation system is unknown.

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