

# Determining the “optimum” slash pine seedling size for use with four levels of vegetation management on a flatwoods site in Georgia, U.S.A.

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**Abstract:** A slash pine (*Pinus elliottii* Engelm. var. *elliottii*) study was established to determine the “optimum” seedling size for use on a flatwoods site in the Coastal Plain physiographic province of Georgia, U.S.A. The optimum seedling is defined as the ideotype that will minimize overall reforestation costs while achieving established goals for initial survival and growth. Initial survival and fourth-year performance were examined in relation to (i) method of site preparation, (ii) herbicide application, and (iii) seedling class (based on root-collar diameter) and to associated establishment costs. Seedling class greatly influenced survival with large-diameter classes (8.5–11.5 mm) exhibiting the best survival (87–99%). Seedlings with 4.5-mm diameters averaged 75% survival. A second bedding pass (double bedding) reduced grasses and woody shrubs, and the herbicide imazapyr reduced grasses and herbaceous broadleaf weeds. Neither treatment improved pine survival. Use of 9.5 to 11.5-mm seedlings (without double bedding) produced larger trees 4 years after planting than 4.5-mm seedlings with double bedding. A simple cost analysis indicated the optimum seedling would be considerably larger (9.5–11.5 mm) in diameter than the “target” seedling (4.5 mm) typically produced at slash pine nurseries. For each dollar invested in establishment, planting the optimum pine seedling on this site resulted in greater gains in early survival and growth than either double bedding or use of imazapyr.

**Résumé :** Une étude a été établie en vue de déterminer la taille optimale de semis de pin de Floride (*Pinus elliottii* var. *elliottii*) pour les plateaux de la province physiographique de la plaine côtière de la Géorgie, aux États-Unis. La notion de semis optimum vise à minimiser les coûts globaux du reboisement tout en atteignant les objectifs visés de survie et de croissance initiales. La survie initiale et la performance après 4 ans ont été étudiées en fonction de (i) la méthode de préparation de terrain, (ii) l'application d'herbicides et (iii) la catégorie de semis (sur la base du diamètre au collet) et des coûts d'établissement qui en résultent. La catégorie de semis a grandement influencé la survie, les plus grands diamètres (8,5–11,5 mm) présentant les meilleurs taux de survie (87–99%). Les semis de 4,5 mm de diamètre présentaient des taux moyens de survie de 75%. Un second exhaussement du sol (double exhaussement) a réduit la présence des graminées et des arbustes et l'herbicide imazapyr a réduit les graminées et les herbacées latifoliées. Aucun de ces traitements n'a amélioré la survie des pins. L'utilisation de semis de 9,5–11,5 mm (sans double exhaussement) a produit des arbres plus gros 4 ans après la plantation que la plantation de semis de 4,5 mm avec double exhaussement. Une analyse simple des coûts indique que le semis optimum serait nettement plus gros (9,5–11,5 mm) en diamètre que les semis de pin de Floride produits selon les normes (4,5 mm) par les pépinières. Pour chaque dollar investi dans l'établissement, la plantation de semis optimaux de pin sur cette station a résulté en gains plus importants en termes de survie et de croissance que le double exhaussement ou l'utilisation d'imazapyr.

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## Introduction

Bareroot seedlings from southern pine nurseries can have an average root-collar diameter (RCD) at lifting of less than 4 mm (Barnett and McGilvary 1993; Miller et al. 1995; Cram et al. 1997; Sung et al. 1997). This RCD “target” ex-

ists in part because tree planters prefer small-diameter seedlings, and seedlings are less expensive to produce when grown at high seedbed densities. A shallow planting hole will usually accommodate small roots while preparing a wide and deep planting hole by hand would reduce planter productivity. Since the tree planter's salary is typically not based on high survival or early growth, low field performance of seedlings can result when target seedling characteristics are based mainly on hand-planting efficiency. Therefore, at several nurseries, the target RCD for slash pine (*Pinus elliottii* Engelm. var. *elliottii*) is less than 5 mm (Haack 1988; Duryea 1990; Kainer and Duryea 1990; McGrath and Duryea 1994).

Some regeneration specialists believe planting efficiency should not be the criterion on which seedling characteristics

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are based. Ideally, the “optimum” seedling should be based on reforestation costs associated with various combinations of seedling ideotypes and silvicultural inputs. We define the optimum seedling as the ideotype that will minimize overall reforestation costs while achieving established goals for initial survival and growth. In some cases, use of expensive site preparation to boost the performance of small seedlings will cost more than planting large-diameter seedlings with minimum site disturbance (South et al. 1993, 1995; Zwolinski et al. 1996). Evaluating trade-offs in cost and performance is rarely performed across a range of seedling sizes and for various levels of silvicultural intensity. A performance evaluation (*i*) and cost evaluation (*ii*) were the objectives of this work. For objective (*i*), we test the null hypotheses of no difference in the survival or early growth due to bedding intensity, herbicide (imazapyr) use, or seedling class. In addition, we tested the null hypothesis of no two- or three-way interactions among seedling class, imazapyr, and bedding intensity. For objective (*ii*), we compared early performance with establishment costs and used a break-even economic analysis.

## Materials and methods

Bareroot 1+0 slash pine seedlings were grown at a seedbed density of approximately 200/m<sup>2</sup> at the Rayonier Nursery in Glennville, Ga., U.S.A. In addition to operational nursery practices, extra applications of ammonium nitrate were applied in August and in September. By October, seedlings had received a total of 227 kg N·ha<sup>-1</sup>. Seedlings were hand lifted on October 12, 1991, and were sorted into 1-mm classes based on RCD. Shoot height (distance between root-collar and shoot terminal) was recorded for each seedling. While lifting it was noted that many of the larger seedlings (RCD > 6 mm) came from the two outside drills (i.e., drills 1 and 8). Root pruning after lifting was not permitted.

Fifty seedlings from each seedling class were randomly selected for morphological analyses. After measuring RCD and shoot height, seedlings were dried at 60°C for 48 h and the dry mass of roots and shoots was recorded. Quantified seedling attributes included foliage mass, total shoot mass, root mass, root volume (measured by water displacement), and root-mass ratio (root dry mass/seedling dry mass).

A root growth potential (RGP) test was conducted using four seedling classes (3.0–3.9, 5.0–5.9, 8.0–8.9, and 10.0–10.9 mm). Tests were carried out in a greenhouse, using a hydroponic method described by Ritchie (1985). Seedling roots were washed and all white root tips were removed from the seedlings. There were three replications (aquariums), each tank containing seven seedlings per diameter class. Seedlings were supported over the aquariums by slit rubber stoppers placed around the root-collar. RGP was measured after 28 days as the number of new, white root tips ≥5 mm in length.

The flatwoods site was located in the Lower Coastal Plain physiographic region of the southeastern United States in Clinch County, Georgia (31°3′N, 82°44′W, 57 m). Soils were classified in the Ocilla series, a loamy, siliceous, thermic Aquic Arenic Paleudult that is somewhat poorly drained. In the spring of 1991, a pine plantation was clear-felled and the residual debris was subsequently raked, piled, and burned.

A split-split-plot design was used in factorial combination with five replications. The design included two levels of site preparation, single bedding and double bedding (whole plots); two levels of vegetation control, herbicide application or none (subplots); and 10 classes of planting stock (sub-sub-plots). The single beds were formed in June 1991, while a second bedding pass was conducted

in early October 1991, two weeks before planting. Bedding (Lowery and Gjerstad 1991) was done with a standard bedding plow pulled by a crawler tractor. Beds were approximately 1.5 m in width and mound crests were less than 0.5 m in height. On October, 16, seedlings were operationally machine planted approximately 1.8 m within the rows and 3.0 m between rows. Whole-plots contained eight rows and were 54 m long and sub-plots contained four rows and were 54 m long. The sub-sub-plots were arranged as noncontiguous plots (Loo-Dinkins and Tauer 1987). Each sub-sub-plot contained at least eight measurement trees, and there were no buffer trees between plots. Except for the two smallest classes, the average depth of planting (shoot height before planting – shoot length above the groundline after planting) was 13–15 cm. The herbicide imazapyr was applied operationally at a rate of 105 g·ha<sup>-1</sup> active ingredient as a banded treatment over the top of seedlings in late March 1992.

Competing vegetation was sampled in October of 1992 on three 1-m<sup>2</sup> plots randomly located within each sub-subplot. Clipped samples were dried at 60°C for 48 h, and the dry mass was recorded. Pine survival a year after planting was recorded in December 1992, and fourth-year heights (*H*) and diameters at breast height (DBH) were measured to the nearest 0.1 mm in November of 1995. A biomass index (BI) (Ruehle et al. 1994) per tree was determined by the formula: BI =  $H \times DBH^2$ . Analysis of variance (ANOVA) was used to test hypotheses about treatments and interactions. A split-split-plot ANOVA was used to assess treatment effects on fourth-year heights, DBH, BI per tree, and first-year survival. Only eight diameter classes (4.5–11.5 mm) were used in each ANOVA. For the survival data, an arcsine square-root transformation was performed prior to analysis. A least-squares regression analysis was used to model the relationship between first-year survival and RCD (using eight means).

A break-even analysis was conducted to compare various establishment options (Bentley et al. 1984; Fox 1988). The volume of wood required to “break even” was determined by the formula

$$[1] \quad \text{VOLUME} = \frac{\text{COST}}{\text{STUMP}/(1+i)^r}$$

where VOLUME is volume per hectare, STUMP is stumpage value per cubic metre at harvest age, *r* is harvest age, and *i* is real interest rate. For our analysis, we assumed a stumpage value of \$20/m<sup>3</sup>, a harvest age of 25 years, and a real interest rate of 7%. One establishment option was selected at the base-level case (i.e., single bed, no herbicide, 10.5-mm seedlings). The break-even volume for this option (84.9 m<sup>3</sup>·ha<sup>-1</sup>) was then subtracted from the break-even volumes for the remaining options. The residual value represents the amount of volume required for an alternative option to achieve the same return on investment as the base-level case.

## Results and discussion

### Competing vegetation

The silvicultural treatments resulted in four levels of competing vegetation. One year after planting, plots not treated with imazapyr contained about 10 t·ha<sup>-1</sup> of non-pine vegetation (Schrock 1994). On single beds, there were about 6 t·ha<sup>-1</sup> of grasses (*Panicum* and *Adropogon* spp.), 2 t·ha<sup>-1</sup> of herbaceous weeds, and 2 t·ha<sup>-1</sup> of woody shrubs (mainly *Ilex glabra* [L.] Gray). Plots on double beds contained almost no woody shrubs, 9 t·ha<sup>-1</sup> of grasses, and 1 t of herbaceous weeds.

The herbicide treatment was more effective in reducing weeds on double-bedded plots (4 t·ha<sup>-1</sup>) than single-bedded plots (6 t·ha<sup>-1</sup>). As a result, treated doubled-bedded plots had

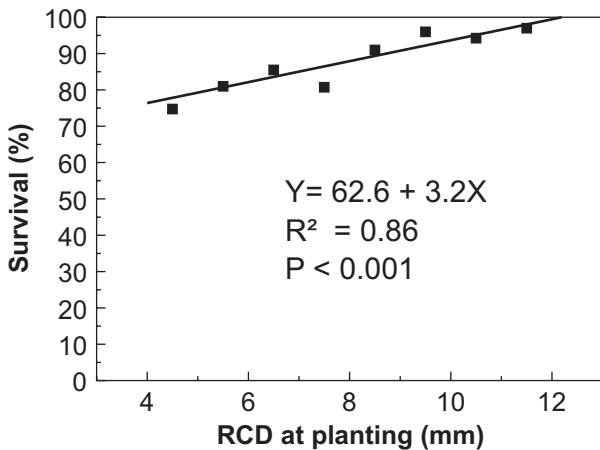
**Table 1.** Average morphological attributes, average planting depth, and root growth potential (RGP) of *Pinus elliottii* by diameter class.

RCD class (mm)	Shoot height (cm)	Dry mass (mg)		Root volume (cm <sup>3</sup> )	Root- mass ratio*	Planting depth (cm) <sup>†</sup>	RGP
		Root	Shoot				
2.5	19	85	910	0.5	0.09	10	—
3.5	24	219	1 910	1.0	0.11	12	6.2
4.5	27	349	3 020	1.4	0.11	13	—
5.5	30	663	3 560	2.7	0.16	14	21.5
6.5	32	1010	5 270	4.2	0.17	15	—
7.5	33	1610	7 340	7.2	0.18	15	—
8.5	32	2110	9 150	9.1	0.19	15	57.6
9.5	32	2670	11 760	11.1	0.19	14	—
10.5	32	2910	12 260	11.5	0.20	14	61.9
11.5	32	3210	15 320	13.2	0.17	15	—

\*Root-mass ratio = root mass/(shoot mass + root mass).

<sup>†</sup>Planting depth = (shoot height before planting) – (shoot length above groundline after planting).

**Fig. 1.** Relationship between first-year survival of *Pinus elliottii* seedlings (planted on a flatwoods site in Georgia) and initial root-collar diameter (RCD).



about 2 t·ha<sup>-1</sup> of grasses, 1 t of herbaceous weeds, and 1 t of shrubs. Single-bedded plots had about 3 t·ha<sup>-1</sup> of grasses, 2 t of shrubs, and 1 t of herbaceous weeds.

By the fourth year after planting, the herbicide treatment appeared to enhance growth of *Ilex glabra* on single-bedded plots. On some flatwoods sites, controlling herbaceous weeds can increase competition from woody shrubs to levels above that on untreated plots (Zutter and Miller 1998; Lauer and Glover 1999).

**Survival**

Slash pine seedling survival increased as seedling diameter increased (Fig. 1). Increasing RCD from 4.5 to 9.5 mm increased survival from approximately 75 to >94%. The equation for percent first-year survival as a function of RCD was

$$[2] \text{ SURVIVAL} = 62.6 + 3.2(\text{RCD})$$

The *R*<sup>2</sup> value is 0.868 (*p* > *F* = 0.0008), and the standard errors for the intercept and slope are 4.2 and 0.5, respectively. Survival was not improved by bedding treatment (*p* = 0.28) or herbicide treatment (*p* = 0.51), and there were no interactions among treatments. The increase in survival for seed-

lings with greater diameter was mirrored by increases in root-mass ratio and RGP (Table 1).

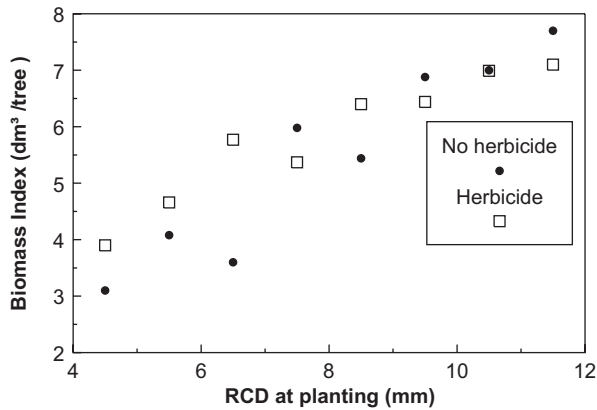
In trials where field survival is not uniformly high, RCD is often positively related to survival (South 1993; Irwin et al. 1998). However, the data presented here differs in important ways than that previously published. Other studies used variation in seedling size when conventional nursery practices were used to grow seedlings resulting in ranges from 2 to 6 mm. This is the first study with slash pine to extend the RCD range to include seedlings >8 mm. Also, in this study, seedlings with large diameters were not excessively tall, and the shoots were not “out of balance” with the roots (Table 1). In other studies, tall seedlings have not survived transplanting as well as shorter seedlings (Venator 1983; Boyer and South 1987; Sluder 1991), which might have been related to a lower root-mass ratio.

Planting depth is often positively related to first-year survival (Blake and South 1991). In this study, seedlings planted only 2.5 cm deep did not survive as well as seedlings planted 15 cm deep (Schrock 1994). Since seedlings in the two smallest classes were generally shorter than other seedlings, they were not planted as deeply (Table 1). Therefore, the low survival (15% for 2.5-mm seedlings and 60% for 3.5-mm) was, in part, due to having their roots 2–4 cm closer to the soil surface. To avoid confounding planting depth with seedling class, these two classes were not used in the analysis.

Seedlings were planted in October (typically the driest month of the year for the region). The lower survival of seedlings from the 4.5- to 5.5-mm classes was due to low soil moisture at time of planting (approximately 9% v/v in October; top 15 cm) followed by below-average rainfall in November (13 mm). Significant rainfall did not occur until mid-December. By January, soil moisture in the top 15 cm of soil had increased to 26% (Schrock 1994). Better survival from the 8.5- to 11.5-mm classes was likely due to a combination of factors including a greater root-mass ratio and a greater RGP of larger diameter seedlings (Table 1).

The survival of southern pine seedlings has been shown to be closely related to increasing the root-mass ratio. Moreover, the capacity to produce new roots soon after transplanting is important to seedling survival (Larsen et al.

**Fig. 2.** Effect of seedling class and herbicide treatment on fourth-year biomass index (height  $\times$  DBH<sup>2</sup>) per tree for *Pinus elliotii* seedlings planted on a flatwoods site in Georgia, U.S.A. There was an interaction between seedling class and treatment with imazapyr ( $p = 0.023$ ).



1986). Until seedling roots establish intimate contact with soil, water uptake is minimized. Moisture stress will likely be less for seedlings with large RCD since they may have a greater root mass, a higher RGP, and are more likely to be planted deeper than seedlings with small roots (Table 1). This may explain why large slash pine seedlings (RCD > 4.7 mm) are more likely to undergo less moisture stress than smaller seedlings when planted in Florida (McGrath and Duryea 1994).

Traditionally, planting of southern pines in October or November has been avoided because small-diameter seedlings typically do not survive rough handling and (or) planting on sites with limited soil moisture. Therefore, transplanting is often delayed until soil moisture is recharged by winter rains. However, unpublished trials have shown that increases in first-season height growth can be obtained by machine planting moist sites in autumn (October and November) rather than delaying planting until February or March. Since some forest products companies have decided to widen their planting window by planting some moist sites in autumn, they will likely obtain higher survival rates if they machine plant optimum seedlings with large root systems. Our data show that even though the conventional target seedlings (with RCD of about 4 mm) would have resulted in less than 75% survival, the larger diameter classes ensured survival to levels acceptable to forest industry (>85%).

Past work using 2+0 loblolly pine (*Pinus taeda* L.) seedlings showed that survival decreased substantially as compared to 1+0 seedlings (Lyle et al. 1958; McLemore 1985). This was likely due to poor root-mass ratios from growing seedlings too long at high seedbed densities. Previous to our study, seedling sizes from 6 to 12 mm for 1+0 slash pine were not considered in research tests in the southeastern United States because of concern about root balance of larger individuals (and perceived planting difficulties). However, hand-lifted, *Pinus radiata* D. Don seedlings grown at low seedbed densities, with RCD of 6–12 mm are considered to be ideal for hand planting in New Zealand and Australia (MacLaren 1993). Our data suggest the same RCD

**Table 2.** Effect of seedling class at planting on initial survival and on fourth-year field performance of *Pinus elliotii*.

RCD at planting (mm)	Survival (%)	Height (cm)	DBH (cm)	Biomass index (dm <sup>3</sup> /tree)
<b>Double bedding</b>				
4.5	76	247	3.0	3.7
5.5	83	284	3.3	5.3
6.5	86	307	4.0	5.8
7.5	84	315	4.1	6.8
8.5	96	314	4.0	7.3
9.5	99	334	4.4	7.9
10.5	95	336	4.4	8.1
11.5	99	344	4.5	8.2
<b>Single bedding</b>				
4.5	74	255	3.0	3.4
5.5	79	256	2.8	3.5
6.5	85	259	3.0	3.5
7.5	78	279	3.4	4.6
8.5	87	279	3.3	4.6
9.5	94	312	3.6	5.4
10.5	96	310	3.7	5.9
11.5	95	325	4.0	6.6

range is desirable for hand-lifted and machine-planted slash pine seedlings in Georgia.

#### Linear or curvilinear growth response?

The relationship between initial RCD and early growth appears to be curvilinear (Fig. 2). If this proves to be the case, then there would be a point of diminishing returns in regards to planting larger and larger stock. For example, on double-bedded plots, there are minimal differences in size between seedlings in the range of 9.5–11.5 mm (Table 2). Although not yet conclusive, this indicates there is a biological limit to achieving gains from planting larger stock. This limit might be related to how many roots can be effectively removed from a bareroot nursery bed (Table 1). Hand lifting seedlings (as done in this study) will likely retain more roots on large seedlings and cause less damage to the stem than machines with belt-lifters. At some nurseries, large reductions in outplanting survival resulted when slash pine seedlings were lifted with machines (Barnard et al. 1980).

#### Early growth compared with silvicultural treatments?

Fourth-year heights and DBH were not significantly increased by double bedding or imazapyr treatment. Since the size range in diameter classes was large, and the degrees of freedom for the error term was high, diameter class had a significant effect on all measured attributes (Table 3). When comparing the average height for the 4.5-mm class (251 cm) and the 10.5-mm class (323 cm), the difference was 72 cm (Table 2). In contrast, the pooled differences in height due to double-bedding and herbicide treatment across size classes were 27 and 6 cm, respectively (Table 4). Likewise, the increases in DBH due to seedling class (4.5 vs. 11.5 mm), double bedding, and herbicide were 12, 6, and 1 mm, respectively. For this study, planting 10.5-mm seedlings on single-bedded plots (with no herbicide) produced as much

**Table 3.** Probability of a greater *F*-statistic for first-year field survival (transformed) and fourth-year height, diameter at breast height (DBH), and biomass index of *Pinus elliottii* seedlings.

Source	Survival	Height	DBH	Biomass index
Replication	0.766	0.035	0.208	0.538
Bedding (B)	0.364	0.136	0.074	0.148
Herbicide (H)	0.455	0.690	0.727	0.720
B × H	0.177	0.812	0.716	0.533
Seedling class (S)	<0.001	<0.001	<0.001	<0.001
B × S	0.786	0.327	0.255	0.156
H × S	0.977	0.599	0.086	0.023
B × H × S	0.412	0.702	0.436	0.495

BI as 4.5-mm seedlings planted on double-bedded plots and treating with a herbicide (data not presented). Obviously, on some sites, growth gains from planting large-diameter stock after moderate site preparation can be as great or greater than growth gains from more intensive silvicultural treatments using common nursery stock.

#### Interactions with silvicultural treatment?

There were no interactions between bedding intensity and seedling class, and there were no three-way interactions (Table 3). However, for BI there was an interaction between seedling class and herbicide treatment ( $p = 0.02$ ) (Table 3, Fig. 2). This interaction may have been of rank since there were four rank changes. However, within the range of 4–7 mm, the interaction is similar to one reported for loblolly pine (Mitchell et al. 1988). Overall, biomass gains appear to be additive when combining larger planting stock with double bedding plus imazapyr.

#### Identifying the optimum seedling

There can be significant morphological differences between a “plantable,” target, and optimum bareroot seedling. A plantable slash pine seedling can have a 3-mm RCD. For some forest regeneration organizations, the RCD for the target seedling is slightly larger (about 4.5 mm) and represents the average for a given nursery. However, the optimum seedling might have a RCD of 8–10 mm. Although the target seedling and the optimum seedling are often different, for some organizations that produce large-diameter stock, they are one and the same.

Before an optimum seedling can be defined, a regeneration forester has to set minimum goals for both initial survival and early growth. Although the goal will depend on overall management objectives, higher performance expectations will typically require improved seedling morphology. For example, if an organization accepts slow initial growth and is concerned only with achieving at least 70% survival, then the target seedling will have a RCD of about 4.5 mm (Fig. 1). However, if a reasonable height or volume growth goal is included, then the target seedling will typically have a larger RCD and a larger root mass.

Once minimum performance levels are set, an analysis of regeneration costs is required to define the optimum seedling. Regional costs of site preparation, herbicide treatment, and machine planting can be obtained from surveys. For ex-

**Table 4.** Mean effect of bedding and herbicide on initial survival, height, diameter at breast height (DBH), and biomass index (BI) of *Pinus elliottii*.

Treatment	Survival (%)	Height (cm)	DBH (cm)	BI (dm <sup>3</sup> /tree)
<b>Soil cultivation</b>				
Single bedding	75	303	3.3	4.5
Double bedding	80	276	3.9	6.3
<b>Herbicide</b>				
No herbicide	78	287	3.5	5.2
Imazapyr	77	293	3.6	5.6
<b>Soil cultivation + herbicide</b>				
Single bed	77	275	3.3	4.6
Single bed + imazapyr	74	278	3.3	4.3
Double bed	80	297	3.7	5.8
Double bed + imazapyr	80	308	4.0	6.8

ample, the average cost of chopping and bedding in the Coastal Plain was approximately \$222/ha (Dubois et al. 1991). In our analysis the site preparation costs (\$90/ha for constructing a single bed and \$70/ha for an additional bedding pass in October) were below \$222/ha because of an efficient harvest (no need for chopping). The cost of machine planting on this site was about \$118/ha, and the cost of a ground application of imazapyr herbicide was \$80/ha.

Currently, slash pine seedlings (grown at 270/m<sup>2</sup>) can vary in cost from \$30 to \$38 per thousand (Anonymous 1998). Using lower seedbed densities to produce larger seedlings will increase nursery costs. For example, 1+0 longleaf pine (*Pinus palustris* Mill.) seedlings are larger and cost more than 1+0 slash pine seedlings, in part, because they are grown at about one third the seedbed density of slash pine. Since longleaf pine seedlings typically have larger roots (they can average more than 11 mm at the root-collar), they are often lifted by hand. Hand lifting is labor intensive and costs more than machine lifting (Chapman 1986). Because of additional growing and lifting costs, longleaf pine seedlings cost \$50 to \$70 per thousand (Anonymous 1998).

In our simple cost analysis, costs for hand-lifting 8.5- and 10.5-mm seedlings were estimated at \$8 and \$11 per thousand, respectively. This estimate was derived from production rates of 9000 – 12 500 seedlings/person per day at a cost of \$100/person per day. It is assumed that fixed nursery costs amounted to \$20 per thousand seedlings. In addition, the costs assigned to growing, lifting, packing, storing, and shipping 8.5- and 10.5-mm seedlings were \$48 and \$64 per thousand, respectively. The total estimated costs (1991 dollars) assigned to 4.5-, 8.5-, and 10.5-mm seedlings were \$36, \$68, and \$84 per thousand, respectively. However, costs will vary with nursery (Mills and South 1984) since costs depend on factors such as seed efficiency, wages, and production level.

Various combinations of silvicultural treatments and seedling ideotypes can be ranked according to total cost per hectare (Table 5). The optimum seedling is determined by the option that exceeds both survival and growth goals at the lowest cost per hectare. For the site illustrated in Table 5, the optimum seedling has a 10.5-mm RCD since it exceeded the targets with an establishment cost of only \$313/ha. In

**Table 5.** Treatment combinations ranked in order of cost per hectare.

Option	Bedding	Herbicide	RCD (mm)	Both targets achieved?	Cost/ha (\$)	Break-even volume (m <sup>3</sup> ·ha <sup>-1</sup> )
A	Single	None	4.5	No	253	-16
B	Single	None	8.5	No	293	-5
C	Single	None	10.5	Yes	313	—
D	Double	None	4.5	No	323	3
E	Single	Yes	4.5	No	333	5
F	Double	None	8.5	Yes	363	14
G	Single	Yes	8.5	No	373	16
H	Double	None	10.5	Yes	383	19
I	Single	Yes	10.5	Yes	393	22
J	Double	Yes	4.5	No	403	24
K	Double	Yes	8.5	Yes	443	35
L	Double	Yes	10.5	Yes	463	41

**Note:** Optimum combination is option C. Performance targets: survival >85% and fourth year height >3 m. The break-even volume (volume required to achieve a return on investment equal to option C) was calculated using a 7% real interest rate, a 25-year rotation, and a stumpage value of \$20/m<sup>3</sup>. Costs per hectare are as follows: single bed, \$90; double bed, \$160; 4.5-mm seedlings, \$45; 8.5-mm seedlings, \$85; 10.5-mm seedlings, \$105; machine planting, \$118; herbicide treatment, \$80. Stocking was 1250 seedlings/ha. All costs are in 1991 dollars.

contrast, the traditional target seedling of 4.5 mm did not achieve the targets even when investing \$403/ha (option J). According to a break-even analysis, option J would not only have to catch up in growth to option C, but it would also have to increase the mean annual increment at harvest (age 25) by almost 1 m<sup>3</sup>·ha<sup>-1</sup> to achieve the same net present value as option C. Even higher growth gains would be required to break even when assuming a lower stumpage price, a higher discount rate, or a longer rotation.

Although higher volume production can be achieved with greater financial inputs, the volume gained per dollar invested generally tends to diminish as investments increase. This is especially true when extra money is invested after outplanting inferior seedlings. Maximum volume growth at all costs is rarely a realistic operational goal because of limited regeneration budgets.

### Increasing the target seedling

Currently, the RCD for the target seedling varies by region and organization. Overall, morphological specifications for the target pine seedling are much higher in New Zealand than for the southern United States. As a result, most pine nurseries in New Zealand grow stock at seedbed densities near 150/m<sup>2</sup> while many nurseries in the southern United States have seedbed densities greater than 250/m<sup>2</sup>. Some forest regeneration organizations in the southern United States have no early growth goals and, therefore, produce seedlings with an average RCD of just 4 mm. After one growing season in the field, these seedlings may average only 6 mm at the groundline (Barber et al. 1991; Harrington and Howell 1998). In contrast, at least one forest products company now has a goal of producing 1+0 loblolly pine seedlings with an average 10-mm RCD. At some locations, 10-mm seedlings will be larger in diameter at the time of transplanting than 3- or 4-mm seedlings outplanted a year earlier (Barber et al. 1991; Harrington and Howell 1998). After 4 years of growth, 10-mm seedlings might average 50–90 cm taller

than 4-mm seedlings (when both are transplanted at the same time).

Some forest regeneration organizations have established height goals for their southern pine plantations. A goal for several forest products companies now is to achieve a height of 1.5 m in 2 years, 4 m in 4 years, and 7 m in 6 years. To achieve these targets in a more cost-effective manner, some organizations have decided to include morphologically improved seedlings (South 1993) in their regeneration plans.

This work has demonstrated once again that pine seedling classes (based on RCD at time of transplanting) can directly affect early growth after outplanting. This is consistent with other pine studies (Britt et al. 1991; South 1993; South et al. 1993, 1995; McGrath and Duryea 1994; Mason et al. 1996; Zwolinski et al. 1996). Mean height and diameter four growing seasons after planting were strongly related to diameter class at planting (Table 3).

Presentation of this and other work at regional meetings has resulted in several forestry consultants and companies revising their approach to reforestation. There has been a shift away from the idea that the nursery is just a cost center. Some now view the nursery as a money saver where investments in nursery culture can reduce overall establishment costs. More research is needed to determine to what extent further gains can be realized through improved nursery culture. In particular, we need to adopt efficient lifting practices that will retain good root-mass ratios for large-diameter stock.

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