Planting Deep Increases Early Survival and Growth of *Pinus echinata* Seedlings

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Abstract: Two studies were established to determine the effects of planting depth on early performance of bareroot shortleaf pine seedlings (*Pinus echinata*). The studies involved planting seedlings either with the root-collar slightly below the groundline (GL) or with the root-collar planted about 11 cm below the soil surface (DEEP). After transplanting, DEEP seedlings had about 7.9 cm of shoot remaining aboveground. In one study, seedlings were planted in open sand pits where seedlings received 352 mm of rain by April 30. The second study involved planting seedlings in boxes (containing sand) in a roofed shade-house. Without rain, survival of DEEP seedlings in April was 96% which was significantly greater (P>F =0.007) than survival of GL seedlings (67%). With rainfall, survival (95%) was the same for both planting depths (P>F = 0.39). Therefore, planting seedlings with the root-collar level with the soil surface can, in some years, increase mortality. This might help explain why bareroot survival of shortleaf pine in some forest districts averages less than 80%.

Keywords: Survival, shortleaf pine, planting quality, reforestation, seedling quality, transplant stress index.

INTRODUCTION

There are two schools of thought regarding the desired planting depth of bareroot shortleaf pine (*Pinus echinata* Mill.) seedlings. The "surface" school favors placing the root-collar of all pine species either at the soil surface or perhaps a "fraction of an inch" below the surface [1-11]. Some say seedlings are planted correctly when they are placed in the planting slit and then raised up "until the root-collar is level with the soil surface" [11]. In contrast, those from the "plant deep" school favor planting shortleaf pine with the root-collar 8 to 13 cm below the soil-line [12-15]. They want to ensure that the tree planter makes a deep planting hole and that roots are placed deep in the hole in hopes of reaching soil with higher moisture content [14]. Typically when half the stem length is buried, some foliage is buried and this reduces the amount of transpiring foliage. These techniques should increase survival in those years where a drought occurs soon after planting. When planting a 20 cm shoot, this method results in the root-collar being planted below the soil surface with perhaps 7-12 cm of the remaining shoot exposed. Some planting machines can make trenches that are as deep as 40 cm [16], but many hand tree planters prefer making shallow planting holes (< 20 cm deep). Therefore, when practical, many from the "plant deep" school prefer machine planting over hand planted seedlings. For example, on one site in Georgia, operational machine planting resulted in the root-collar about 14 cm below the surface [17].

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When shortleaf pine is planted prior to a drought, in some cases survival may be less than 40% [18]. Fortunately, tree planters can use techniques that increase the chance of surviving a drought. On some sites, container-grown shortleaf pine seedlings have survived better than bareroot stock [19-21]. However, planting container stock (@ 14 cents each), to achieve higher survival, might cost $115 per ha more than bareroot stock (@ 5 cents each).

Alternatively, Williston [22] said that bareroot stock size should be matched to the planting site. He recommended reforestation managers make an appraisal of the subsequent "summer moisture conditions for each area to be planted." If the site was expected to be moist during the summer months, he suggested planting shortleaf pine with 20 to 25 cm shoots. Where limited summer moisture was predicted, he suggested planting seedlings with 10 to 18 cm shoots. However, his recommendation would require either nursery managers grade seedlings (into two height classes), or some designated nursery beds might be top-pruned if seedlings are used on droughty sites. However, reforestation managers can't accurately forecast a spring or summer drought any better now than they could 40 years ago. What is needed is a planting technique that will increase the chance of survival of bareroot stock in dry years but can also be used in years when rainfall is adequate for high survival.

The belief that shortleaf pine seedlings should not be planted deeply is based, not on studies, but primarily on traditional planting guides (many published before 1960). Some claim that planting seedlings deep will kill loblolly pine (*P. taeda* L.) or shortleaf pine [23, 24]. However, not only is this not true, but a review of 14 studies [17] found that planting loblolly or slash pine (*P. elliottii* Engelm.) seedlings deep typically increases survival, especially when seedlings are planted on well drained sites. Therefore, it is unfortunate that only a few planting guides recommend planting the root-collar of bareroot shortleaf pine 8 to 13 cm deep. In fact, one planting guide says that loblolly pine should be planted with the root-collar 5 cm below the surface but that shortleaf pine should be planted at the same level they grew in the nursery. When the response variable is initial survival, we know of no reason why a species by planting depth interaction would exist for these two species.

The terminology used in tree-planting guides is often vague and confusing. For example, some say the correct depth of planting should be 3 to 6 cm "below root-collar" [25]. Others define a seedling as being planted "deep" when the root-collar is placed only 3 cm below the soil surface [26, 27]. In this paper, we will abide by the following definitions. The "root depth" is the distance between groundline and bottom of the roots after planting. The "planting depth" is the distance between the root-collar and the groundline (negative values indicate the root-collar is aboveground). The "correct planting depth" is the depth where survival and early growth are optimized. A "shallow planting hole" is one that is less than 20 cm deep while a "deep planting hole" is greater than 25 cm deep.

MATERIALS AND METHODS

Nursery Culture

Shortleaf pine seedlings from a single half-sib family were operationally grown at the Claridge Nursery in Wayne County, North Carolina (35º 26' N, 78º 01'W; 24 m elevation). Seed (seedlot TN-41-1-110-1-82-01) were sown in beds on 9 May 2011. Seedlings were undercut (15 cm deep) on 12 October 2011 and were lifted on 9 December 2011. There was no top clipping and no lateral root pruning. Seedlings were shipped to Auburn University where they were kept in a cooler (4-5 ºC) until planted. Shoot heights ranged from 8 cm to 33 cm and ground-line diameters ranged from 2 to 10 mm. The average seedling diameter from this nursery was larger than the overall mean for various nurseries that typically produce shortleaf pine (Table **1**).

Outside Study

A planting depth study was established at the Auburn University campus (32º 35' N, 85º 29'W; 205 m elevation) in Lee County, Alabama (Fig. **S1**). The "outside" study involved planting seedlings in four sand-filled pits (each measuring 4 x 5 x 1 m). Each pit (i.e. replication) contained two treatments, and each experimental unit contained 75 trees (5 rows of 15 trees per row). One treatment was planted with the root-collar at or slightly below the groundline (GL), and the other was planted with the root-collar approximately 11 cm below the surface (DEEP). All seedlings were planted using a shovel on 5 January 2012 (without pruning roots). On 3 February, 11 May, and 8 June 2012 the total shoot height (above the soil surface) was recorded. On 29 May 2012, a sample of 15 seedlings from each treatment was excavated and the root-collar diameter (RCD), depth of planting (root-collar to soil surface) and rooting depth (bottom of planted roots to soil surface) were recorded.

Table 1. Summary of Average Root-Collar Diameter (RCD) and Shoot Height of *Pinus echinata* Seedlings from Various Nurseries

Year	Nursery Location	RCD (mm)	Height (cm)	Ref.
2007	Licking, MO	3.3	21	[35]
1978	Licking, MO	3.4	14	[84]
1988	Bluff City, AR	3.8	29	[85]
1985	Alexandra, LA	3.9	16	[34]
1987	Bluff City, AR	4.0	24	[85]
1989	Magnolia, AR	4.2	27	[85]
2006	Delano, TN	4.3	20	[18]
1985	Magnolia, AR	4.4	19	[85]
Average		4.6	22	
1986	Magnolia, AR	4.6	25	[26]
1989	Ft. Towson, OK	4.7	19	[45]
1985	Magnolia, AR	4.7	18	[74]
1976	Brooklyn, MS	5.1	23	[19]
1988	Ft. Towson, OK	5.1	31	[85]
2011	Goldsboro, NC	5.2	19	This study
1986	Magnolia, AR	5.3	21	[85]
2003	Delano, TN	5.5	23	[86]
1977	Brooklyn, MS	5.8	19	[84]
1977	Gilbertsville, KY	6.0	26	[84]

Shade-House Study

A second study was conducted in a solid roofed, shade-house (85% shade). Four wooden boxes (each measuring 1.2 x 1.2 x 0.9 m) filled with sand were irrigated prior to planting and for approximately a week after planting (Fig. **S2**). Each replicate (i.e. box) contained four experimental units (two per treatment) and each experimental unit contained 2 rows of seedlings (ie. 12 seedlings per row). After planting, the groundline diameters (GLD) and total shoot heights (above the soil surface) were recorded on 2 February 2012. Seedlings received no rainfall or irrigation in January through April, but irrigation resumed on 3 May 2012. Survival counts were conducted on 3 April 2012 and shoot heights were recorded on 29 May 2012. To test the effect of seedling diameter on survival, GL seedlings in the shade-house were separated into two roughly equal groups: stock larger (or smaller) than 5 mm GLD.

On 30 May 2012, the shoots of all live seedlings were cut (about 1 cm above the soil surface) and the fresh weight recorded. Sprouting data were collected on 12 June 2012 and sprout heights were measured on 3 August 2012. Each clipped seedling was classified into one of two categories: sprouted or non-sprouted. These data were used to test the hypothesis that planting depth does not affect the ability of shortleaf pine to sprout.

Transplant Stress Index

A transplant stress index (TSI) value was determined for each treatment and replication. TSI is defined as the slope of the linear relationship between shoot height at the beginning of a growth period and the height increment for that period. The procedure requires repeated measures of heights for the same individuals. TSI values for the growth periods January to May (shade-house) or February to June (outside) were obtained using the equation: $h_1 - h_0 = X_1 + TSI_1(h_0)$, where

h_0 = Initial height (in February)

h_1 = Height in May or June

TSI_1 = Transplant stress index for time period 0 to 1

X_1 = the y-axis intercept

Statistical Analysis

Analyses were carried out using the Statistical Analysis System [28]. Analysis of variance (ANOVA) was preformed using the PROC GLM function to test for treatment differences at an alpha level of 0.05. To determine the relationship between seedling diameter and survival, GL seedlings in the shade-house were grouped into two GLD classes (< 5 mm, and $\geq$ 5 mm). A mean survival value was determined for each of the sixteen experimental units. Regression analyses were conducted using the PROC REG function.

RESULTS

Survival

Seedlings in the open study received over 350 mm of rainfall during the months of January through April (Table **2**) while those in the shade-house received no irrigation or rainfall. Regardless of planting depth, survival was excellent when seedlings received rain (Table **3**). However, when seedlings were exposed to a simulated four-month drought, survival was greatly improved by deep planting. In April and May, DEEP seedlings had 27% and 46% better survival than GL seedlings (Table **4**). An interesting observation was that 96% of DEEP seedlings were alive on 4 April 2012 even though soil moisture had been in decline for a period of three months.

Table 2. Precipitation (Rain), Deviation from Normal in mm (DFN), Number of Days with Rainfall > 2.5 mm (Rain Days), Maximum and Minimum Temperature (Celsius), and Solar Radiation (SR) Recorded at Auburn, Alabama in 2012

Month	Rain (mm)	DFN (mm)	Rain Days	Max. Temp	Min. Temp	SR (kJ/m^2)
January	119	-15	9	24.4	-5.0	8600
February	85	-38	6	24.4	-5.6	9943
March	93	-71	8	29.4	4.4	14954
April	55	-54	5	31.1	5.0	18695
May	67	-25	7	34.4	13.3	19163
June	55	-46	2	38.3	13.3	19481

After planting seedlings deep, the amount of shoot exposed varied from 1 cm to 19 cm and averaged 7.8 cm (shade-house) or 7.9 cm (outside). One might question how deep is too deep in regards to survival. To address this question, we examined the survival of DEEP seedlings that had less than 3 cm of shoot exposed. In the outside study, all seedlings that had 1 cm (n=8) or 2 cm (n=7) survived. In the shade-house study, there were no 1 cm shoots after planting. All seedlings that had 2 cm of shoot (n=5) exposed were living on 29 May 2012. Of the 16 seedlings with 3 cm shoot exposed, 19% were dead on 29 May 2012.

The hypothesis that seedling size does not affect survival was rejected (P>F = 0.0233). The survival of the smaller

Table 3. The Effect of Planting Depth on Survival (May), Initial Height (HT), Transplant Stress Index (TSI), Heights in May and June, and Height Growth (February to June) of *Pinus echinata* Seedlings Planted in Full Sunlight

Depth of Root-Collar	Survival (%)	HT (cm)	TSI	May Height (cm)	June Height (cm)	Growth (cm)
Just below surface	96	17.4	-0.06	28.7	33.3	15.8
11 cm below surface	95	8.7	-0.07	26.7	31.9	23.2
LSD (α =0.05)	5.3	2.0	0.19	1.7	2.3	4.3
P > F value	0.391	0.0008	0.8856	0.0346	0.1515	0.0117

Table 4. The Effect of Planting Depth on Initial Groundline Diameter (GLD), Initial Height (HT), Survival (April 3 and May 29), Transplant Stress Index (TSI), Height in May, Height Growth (February to May), Shoot Fresh Weight (May), Sprouting (June) and Sprout Height (August) of *Pinus echinata* Seedlings in the Shade-House

Depth of Root-Collar Below Surface	GLD (mm)	HT (cm)	April Survival (%)	May Survival (%)	TSI	May Height (cm)	Growth (cm)	Shoot Weight (g)	Sprouting (%)	Sprout Height (cm)
1.9 cm	5.2	17.5	67	28	-0.27	22.0	7.1	9.2	90.5	12.3
11 cm	2.9	7.9	96	74	-0.52	17.2	9.9	6.9	92.9	16.5
LSD (α =0.05)	0.3	1.7	19.5	14.6	1.4	2.1	1.9	1.6	13.5	1.8
P > F value	0.0001	0.0001	0.0001	0.0070	0.5284	0.0004	0.0075	0.0071	0.7045	0.0004

seedlings was 24 percentage points greater than for the larger seedlings (Table **5**).

Table 5. The Effect of Initial Seedling Size (February) on Survival (May) and Shoot Fresh Weight (May) when *Pinus echinata* Seedlings were Planted with the Root-Collar Near the Surface in the Shade-House

Seedling Size	Initial Height (cm)	Initial GLD (mm)	Survival (%)	Shoot Weight (g)
Large (n=95)	20.4	6.6	17	13.1
Small (n=97)	14.8	3.9	41	8.6
LSD (α =0.05)	--	--	17	7.3
P > F value	--	--	0.0233	0.1405

GLD = Groundline Diameter.

Transplant Stress Index

A negative TSI value indicates transplanting stress, while positive values indicate little or no stress. Negative TSI values are the norm for the first year after planting pine. As expected, none of the TSI values from either study were positive (Tables **3** and **4**). The TSI values from the shade-house (-0.39) were lower than the average for the seedlings grown outside (-0.07). The depth of planting did not have an effect on TSI values in either study (P > F > 0.5).

Initial Growth

In both the shade-house study and in the open study, the growth of GL seedlings (Fig. **S3**) was less than DEEP (Fig. **S4**) seedlings (P>F < 0.012).. For DEEP seedlings in the open, early growth (by June) averaged 23.2 cm (Table **3**). The amount of additional growth was sufficient so there was only a 1.4 cm difference in total height (P>F = 0.15). Growth of DEEP seedlings in the shade-house was 10 cm by May (Table **4**).

Sprouting

The hypothesis that planting seedlings deep reduces sprouting ability was not supported (P>F = 0.70). The sprouting of clipped seedlings in both treatments was greater than 90 % (Table **4**; Fig. **S5**). The early height growth of the sprouts was greater for DEEP seedlings.

DISCUSSION

According to Cheyney [29], "The directions for the planting of a tree have become more or less stereotyped and have been copied for so many years that it is practically impossible now to say on what the directions are based…." The same can be said for many of the current recommendations regarding the "correct" planting depth for shortleaf pine. Most planting depth recommendations for pine are similar to those made in the United Kingdom during the 19th century [1]. Several authors make claims without providing the reader with any evidence that research trials actually support the claims made in the guides. The current study might be the first depth of planting study for shortleaf pine in the southern United States, and hopefully it will prove useful to authors of tree planting guides.

Survival

Although many planting guides for pines currently recommend planting with the root-collar at or only slightly below the surface, we found no adverse effects of planting the root-collar 11 cm below ground when shortleaf pine seedlings were planted outside in sand. Planting seedlings deep increased survival by 27 to 46 percentage points, when the seedlings were planted in the shade-house just prior to an extended drought.

The greater survival of seedlings planted deeply was likely due to; (1) less exposed foliage and (2) roots not drying out as quickly. The amount of foliage exposed after planting will affect how much moisture is lost from evapotranspiration [25]. Most nursery managers agree that pine seedlings that are taller and have more foliage generally do not survive as well as properly top-pruned seedlings [30]. For example, tall shortleaf pine planted in Missouri during the fall of 1937 had 37% survival while shorter, top-pruned seedlings had 76% survival [31].

It is well known that the rate of moisture depletion during the first 20 days of a drought is much greater for the top 13 cm of soil than it is for the next 13 cm of soil [32]. It is also known that soil moisture is a key factor in determining a seedling's ability to produce new roots [33]. Therefore, in order for shortleaf pine to survive transplanting into coarse-textured soil, the root system in the upper soil profile must be able to be replenished by rainfall (as in the outside study) or the roots need to be deep enough to contact lower soil profiles that a higher level of moisture (as in the shade-house study).

Previous studies indicate a general increase in survival when loblolly pine and slash pine seedlings are planted deep on sites where survival is not high (Fig. **1**). This relationship suggests no gain in survival when the average survival of GL seedlings is >87%, but when GL seedlings achieve only 60% survival, deep planting might increase survival by 10 percentage points. In addition to planting depth, optimal survival of shortleaf pine depends on initial seedling size, site preparation method, month of planting, and rainfall after planting.

Seedling Size

Opinions vary regarding the target bareroot shortleaf pine for optimum survival. Some recommend seedlings be culled if the RCD is less than 4 mm [6] while others recommend a minimum RCD of 1.6 mm [34]. Therefore some nursery managers produce bareroot shortleaf pine seedlings with root-collars that average less than 4 mm in diameter while others produce seedlings with diameters that are greater than 5 mm (Table **1**).

Several researchers have reported that large-diameter, bareroot shortleaf pine seedlings survive transplanting better than small-diameter stock. On a ridge-top in Tennessee, survival was about 8 percentage points greater for ≥5 mm RCD seedlings than for seedlings with diameters smaller than 3.7 mm [18]. Kabrick *et al.* [35] also reported better survival for 5 mm than for 2 or 3 mm seedlings. When comparing 2.5 mm RCD seedlings with 5.1 mm seedlings, survival of the larger stock was 16 to 29 percentage points greater in Missouri [36] and 3 to 19 points greater in Indiana and Arkansas [37]. The greater survival potential for the larger diameter seedlings may partly explain why several nursery managers choose 5+ mm as the target diameter for shortleaf pine (Table **1**).

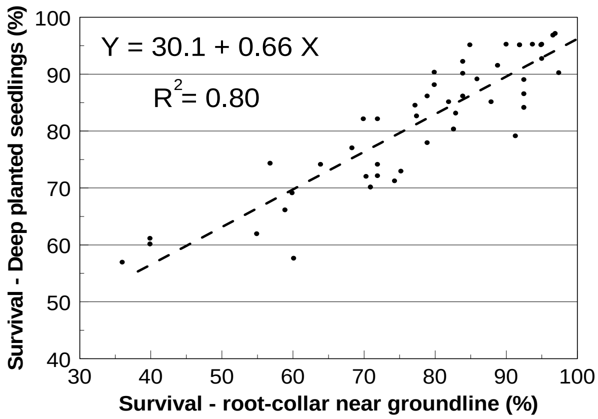

Fig. (1). A generalized response of loblolly pine and slash pine seedlings to deep planting on well-drained sites (n = 48). When initial survival is 60% (for seedlings planted with the root-collar at or just below the soil surface), one might expect deep planting to increase survival to 70%. See supplementary Table **S1** for more details.

The effect of seedling size on survival in the shade-house was opposite. We observed lower survival when seedlings had a GLD of 5 mm or greater (Table **5**). This contradiction might be the result of a site by seedling size interaction. Seedlings in the shade-house study were immediately exposed to an extended drought with continuous shade (likely resulting in a reduction in early root growth). In contrast, the field studies received natural rainfall and full sun, both conducive to new root growth. Under natural conditions, survival might be greater with > 5 mm RCD seedlings because of greater root growth [38] and a greater chance of successfully competing with weeds. When seedlings have a limited amount of new root growth (soon after transplanting), the seedlings that have more transpiring foliage would, in theory, suffer more transplant stress. Indeed, for GL seedlings, there was a relationship between shoot height and GLD after planting. The regression equation was: ht = 8.49 + 1.74g, where ht = shoot height (cm) in May and g = GLD (mm) ($r^2 = 0.30$) ($P < 0.0001$) (n = 192). This indicates that a shoot of an 8 mm diameter seedling (@22 cm) would be more than 80% taller than an average shoot from a 2 mm seedling (@12 cm). For loblolly pine, taller seedlings (after planting) tend to have lower survival when conditions for high survival are not favorable [39].

Site Preparation

To increase the probability of survival, some reforestation managers will "rip" the soil to a depth of 40 to 60 cm several months prior to planting [14, 16, 40-44]. When seedlings are planted in the ripped zone, the time required for hand planters to make a 25 cm deep hole is reduced [40, 44]. In some sites, ripping prior to planting can increase survival by 4% [42] and in others it might increase survival by 20% [14, 41]. In cases where seedlings are not planted in the rip, there will likely be no improvement in depth of planting. On one site in Oklahoma, planting in the furrow bottom or on an adjacent location made no difference in second year survival, but on another site, survival of seedlings planted in the furrow was increased by 15 percentage points [45].

Controlling herbaceous weeds can increase the level of soil moisture available to seedlings [46] and higher soil moisture can be important, especially for regions subject to spring and summer droughts. In cases where seedlings are planted in January or February and when soil moisture is adequate during the first six months of the year, then initial survival will likely be high [e.g. 46]. In the outside study, soil moisture was mainly affected by rainfall and evapotranspiration of the pine seedlings since few weeds were present. The lack of treatment differences in our trial might be, in part, due to a lack of competition from woody and herbaceous plants.

Month of Planting

The month of planting shortleaf pine will have a significant effect on survival. When planting bareroot seedlings in the month of April [41, 47] or May [18], survival has been less than 40%. The results of our outside study may have shown treatment differences if we planted bareroot shortleaf pine in April instead of in a more traditional month. Survival rates greater than 80% can be expected during the months of November to February [47, 48].

Planting Tool

For shortleaf pine, loblolly pine and slash pine, good survival of bareroot stock depends on the depth of the planting hole which depends on the type of equipment used. Where feasible, machine planting is preferred since in dry years, survival is typically greater when seedlings are planted by machine. Operators of machine planters generally do not complain when planting 5 to 10 mm (RCD) seedlings with large root systems. Unfortunately, many sites planted to shortleaf pine are planted without either ripping or machine planting.

Various tools can be used when planting large bareroot stock by hand. The long handle planting shovel (TT 2-0) can make a hole that is 28 cm deep. Planting crews experienced with using planting shovels can plant more than 140 seedlings per person per hour [12, 49]. Barry Malac was a pioneer member of the "plant deep" school [50], and he recommended using a dibble with a 30 to 35 cm blade when planting "Grade 1" seedlings [51]. In contrast, a new OST planting bar can make a hole that is 25 cm deep and some worn ones will make a 20 cm deep hole. Hand planters typically prefer to plant seedlings with small roots since they can use a tool that does not make a deep planting hole.

Several authors of tree planting guides have discussed the desired depth of the planting hole. Those from the "surface" school might recommend making a hole that is 15 to 20 cm deep [23]. However, when shortleaf pine roots have a length of 25 cm, this means either pruning roots to avoid bent root systems [9] or bending 5 to 10 cm of the roots in an L-, J-. or U-root configuration. When faced with these two options, many tree planters will prune the roots instead of making a deeper hole. Taproot length of a sample of seedlings from the outside study ranged from 14 cm to 34 cm (average 20.6 cm). Pruning roots just before planting will reduce the amount of time required to make a hole [52], but root pruning by tree planters can decrease early survival and growth [52, 53]. Even stripping fine roots can reduce both new root growth and seedling survival [54, 55]. One possible reason why survival was high in our open study was because pruning and stripping of roots was not permitted.

Bent Roots

Taproot length from the outside study ranged from 14 cm to 34 cm (average 20.6 cm). This means that if the taproot was to be kept straight, and the root-collar was planted 11 cm deep, then the planting hole would range from 25 cm deep (for a 14 cm taproot) to 45 cm deep (for a 34 cm taproot). For the outside study, the depth of the hole was estimated to average 21 cm for the DEEP treatment and 17 cm for the GL treatment. In other words, some root distortion was expected for all seedlings planted in the DEEP treatment as well as most of the seedlings in the GL treatment. Little and Somes [56] reported that shortleaf pine can overcome most distortions in their root systems. They excavated seedlings and found only one planted shortleaf pine out of 24 developed a relatively "normal" root system.

It is known that a high percentage of planted seedlings (40 to 80%) in the southern United States can be classified as having deformed roots [56-62]. However, just because a planted pine seedling has a bent taproot or compressed lateral roots, this does not mean its performance will be less than seedlings that originate from direct seeding or seedlings planted in a slit with an I-root [63]. On four sites in Arkansas [61], 27% of the shortleaf pines that originated from seed had a turn or bend in the taproots (likely due to rocks and compact soil layers). Therefore, a bent taproot can be "natural" (if occurring after transplanting) or "human-made" (if occurring during transplanting).

In New Jersey, a researcher reported no harmful effects of planting L- or J-roots in "poor slits" on survival or early growth of shortleaf pine seedlings [64]. This is in agreement with most trials where bent roots of other pine species have been planted in deep holes [63, 65, 66]. Little [64] excavated shortleaf pines that were planted with an L-, J-, or U- root and concluded that although some roots were twisted and others had few roots on one side, "all the excavated seedlings had developed spreading root systems indicating that root systems had largely recovered from planting damage."

Bent Stems

It is known that a high percentage of shortleaf pine seedlings have a "crook" on the stem near the groundline. Lilly and others [67] found that 40% of planted seedlings may exhibit a strong crook (i.e. parallel to the ground at some point and often buried by soil). As far as we know, no tree planter has been instructed to cull shortleaf pine seedlings if they see a bent stem near the root-collar. Likewise, we doubt any forester has suggested that factors that decrease sawtimber quality (e.g. compression wood or stem sinuosity) would be affected by planting shortleaf pine seedlings with crooks. In contrast, we know of tree planters who have been penalized for planting a seedling with a bend in the taproot (due to placing the root-collar 11 cm below the surface). In fact, some say that planting the crook below ground might affect the ability of shortleaf pine to sprout.

As far as we know, there are no empirical studies to show that planting the crook 11 cm deep will prevent shortleaf pine from sprouting. Even so, some recommend planting the crook near the soil surface since they fear that planting the crook deep might reduce sprouting after clipping by deer or rabbits. Bell [68] brought this to our attention and said that more research on this topic is needed. To address this concern, all live seedlings in the shade-house were clipped on May 30th and sprouting began before June 12th. We observed no reduction in sprouting due to planting the crook deep (Table **3**). Our results do not support the hypothesis that planting seedlings deep will either (1) increase their chance of dying (a claim found in some tree planting guides) or (2) decrease their chance of sprouting.

Growth

Early growth of loblolly pine and slash pine seedlings that are planted deep is typically greater than for seedlings planted with the root-collar at the soil surface [17]. In most cases, the 10 to 13 cm difference in initial height has vanished by the third year after transplanting. We also found an increase in growth by planting shortleaf pine seedlings deep. In the shade-house study, DEEP seedlings that survived the drought grew an extra 2.8 cm by the end of May. This is remarkable considering the seedlings had not received any rainfall. In the outdoor study, seedlings in both treatments grew but the DEEP seedlings grew an extra 6.6 cm by the end of May. As a result, they were, on average, only 1.4 cm shorter than GL seedlings in June.

Except for species like longleaf pine (*P. palustris* Mill.) where planting the root-collar 3 cm deep can reduce survival [69], it is generally not harmful to plant pine seedlings so that only the terminal and a few needles are exposed. On some sites this practice has been beneficial [14, 50, 70-72]. However, there are some exceptions. This planting method is not recommended when the water table is near the surface or on poorly drained sites [73].

For eight DEEP seedlings that had 1 cm of shoot exposed in the outside study, the average growth was 16.1 cm, and one grew 30 cm. For seedlings with 2 cm of shoot exposed (n=7), average growth was 16.6 cm, and one seedling grew 23 cm. In the shade-house study, the seedlings that had 2 or 3 cm of shoot exposed (n = 21) averaged 11 cm in growth, and one seedling grew 19 cm. These results suggest that placing roots closer to moist soil can enhance growth even when only 1 to 3 cm of shoot is exposed.

In some cases, growth of bareroot shortleaf pine for the entire first year may be 34 cm [46] and in others it might only be 8 cm [26], 10 cm [35], 15 cm [18] or 17 cm [74]. In contrast, growth of DEEP seedlings was already 23 cm by mid-June (Table **3**). The reason for good early growth for this treatment might be due to several factors, including greater than average stock size (Table **1**), deeper planting depth (Table **3**), a lack of weed competition, optimal timing of rain (Table **2**) and transplanting in January.

Transplant Stress Index

The TSI method has been used to evaluate the early performance of pines in Spain [75-77], New Zealand [78], England [79] and South Africa [80] and this method may be useful for shortleaf pine as well. Although this is the first time that TSI values have been published for shortleaf pine, TSI estimates can be made for certain reports where initial height and subsequent height are reported. For example, using six family means, first-year TSI values of -0.5 and -0.6 were generated for bareroot and container-grown shortleaf pine, respectively [data in 26]. Survival for the same families on this site was excellent and averaged more than 95%.

FUTURE RESEARCH

Although seedling survival can be increased by planting seedlings in a deep planting hole, most researchers do not report planting depth for treatments such as ripping or bedding. Therefore, one might ask if increases in survival observed from these treatments are simply due to deeper planting by hand planters, or to some other soil-related factor. In cases where survival is increased by 14% following bedding [81] or 10 to 30% following ripping [41], how much of this increase might be simply due to planting seedlings deeper on prepared areas? Likewise, when machine planting increases seedling survival by 4 to 23% [82, 83], is this gain simply due to planting seedlings deeper? Assuming a linear relationship, planting seedlings just 7 cm deeper than "normal" might increase survival by 8% (in some situations). This might be sufficient to explain half to all of the gain in survival from ripping or machine planting. We suggest that researchers document planting depth in order to ascertain why certain treatments increase early survival. In situations where funds for artificial regeneration are limited, some might find that deeper planting of shortleaf pine is a relatively inexpensive way to increase the probability of survival.

CONCLUSIONS

When soil moisture in the upper soil profile becomes a limiting factor, planting of bareroot shortleaf pine seedlings deep (e.g. with the root-collar 11 cm below the surface), can increase the chance of survival on well-drained sites. Even so, some planting guides place more emphasis on keeping the tap-root straight than on making a deep planting hole (so the root-collar can be planted 10 to 15 cm deep). This is a common depth for machine-planted seedlings. Planting guidelines for shortleaf pine should be rewritten to: (1) emphasize the "proper" depth of planting (to increase seedling survival as opposed to conforming to tradition), (2) explain the site/planting depth interaction for survival, (3) de-emphasize intuitive beliefs that roots should look "normal" after planting, (4) eliminate any mention of the "pull-up" planting technique for species like shortleaf pine, (5) explain the factors which often cause machine planting to increase survival, (6) discourage pruning roots and root stripping by tree planters, and finally (7) references to field studies should be included to support the tree planting recommendations.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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SUPPLEMENTARY MATERIAL

Supplementary material is available on the publisher's web site along with the published article.

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