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Effect of container type and seedling size on survival and early height growth of *Pinus palustris* seedlings in Alabama, U.S.A.

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Abstract

Three hardwall container types, one styroblock® container type, and two mesh-covered plugs were used to grow longleaf pine (*Pinus palustris* Mill.) seedlings at a nursery in Louisiana. In 2001, these container types, along with bare-root seedlings (from a different seed source), were outplanted on two old-field sites and two cutover sites. There were significant site by treatment interactions. Second-year survival was higher on cutover sites than on old-field sites. Root-collar diameter of container-grown stock was positively related to root growth potential (RGP) and height after two growing seasons. Container-grown stock with the lowest RGP exhibited the lowest overall seedling survival. On three sites, field performance of seedlings grown in mesh-covered plugs was less than seedlings grown in other types of containers. For styroblock® trays, treating cell walls with copper increased RGP but did not affect field performance. Increasing the spacing between container cells increased diameter and height after two growing seasons. A root bound index (RBI) was developed and was calculated for each container seedling by dividing root-collar diameter by the diameter of the container cell. Survival was low when RBI was greater than 27%. Although large-diameter bare-root stock can be advantageous as far as survival and growth is concerned, the same may not be true for containers. Some 7-month old container seedlings might become too large for some container types.

Keywords: Longleaf pine; Hardwall containers; Mesh-covered plugs; Bare-root seedling; Seedling quality; Copper coating

1. Introduction

In 1984, nearly all of the 10 million longleaf pine (*Pinus palustris* Mill.) seedlings planted in the southern United States were produced in bare-root nurseries. Two decades later, about 48 million

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Table 1
Survival of container-grown and bare-root seedlings of *P. palustris* in the southern United States

Years after planting	Container RCD (mm)	Bare-root RCD (mm)	Container survival (%)	Bare-root survival (%)	Difference in survival (%)	Reference
1	–[a]	–	56	2	+54	McGuire and Williams (1998)
4	–	–	80	37	+43	Cram et al. (1999)
5	–	–	84.5	43.5	+41	Boyer (1989)
4	–	–	85	45	+40	Cram et al. (1999)
1	10	14.1	88.3	55	+33.3	Rodríguez-Trejo and Duryea (2003)
5	–	–	79	50	+29	Goodwin et al. (1982)
4	–	–	83	57	+26	Cram et al. (1999)
4	–	–	90	65	+25	Cram et al. (1999)
5	–	–	90	64.8	+25.2	Boyer (1989)
5	–	–	93	69	+24	Goodwin et al. (1982)
5	–	–	74.5	52.2	+22.3	Boyer (1989)
3	–	–	80	58	+22	Goodwin (1976)
1	3.9	–	36	14	+22	Amidon et al. (1982)
1	2.2–3.0	–	85	70	+15	Goodwin (1980)
1	–	–	24.6	10.3	+14.3	Rodríguez-Trejo et al. (2003)
5	–	–	80	67	+13	Goodwin et al. (1982)
5	–	–	55	42.5	+12.5	Boyer (1989)
5	–	–	78	69	+9	Goodwin et al. (1982)
1	4.0	–	84	79	+5	Barnett (1991b)
1	5.2	–	79	79	0	Barnett (1991b)
1	11	14.1	50	55	−5	Rodríguez-Trejo et al. (2003)
Average			75.9	53.5	22.4	

[a] Measurements not reported.

container-grown longleaf pine seedlings were produced which amounts to more than 70% of the total production. This rapid shift in stock type occurred because survival of this species is often less than desired when bare-root stock is planted (Boyette, 1996). Use of container stock not only increases the average survival by perhaps 22% points (Table 1), but the difference in survival from bare-root stock tends to be greater on adverse sites (Fig. 1).

In 1975, only three container nurseries were growing longleaf pine but by 2000, this number exceeded 40 nurseries (Hainds, 2002). As a result, several container types are used in Southern nurseries (Barnett and McGilvray, 2000). This provides a challenge to researchers since seedling quality research on one specific container type might not be applicable to others. What is needed is a way to measure the performance potential of a container seedling quickly and objectively, regardless of the brand of container (Tinus and Owston, 1984).

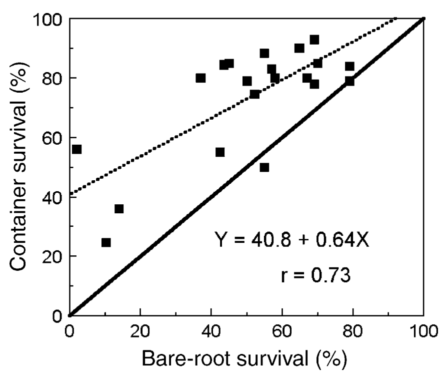

Fig. 1. Effect of stock type on survival of *P. palustris*. Each point represents one comparison between container stock and bare-root stock. Adverse sites are considered to be sites where survival of bare-root stock is less than 70%. Solid symbols ($n = 21$) are data from the literature. The solid line represents no difference in survival between stock types. Points above the solid line are cases where the survival of container seedlings was greater than that for bare-root seedlings.

Research on producing seedlings in tubes (cylindrical overlapping wrap of hard plastic) helped managers learn that the seedlings were too small and that ribs were needed to keep lateral roots from circling the pot and causing problems in subsequent development (Tinus and Owston, 1984). Although performance data exist for some older (no longer used) container types, published data on newer container types for longleaf pine are rare.

Research on seedling quality of container-grown longleaf pine has been limited mainly to comparing stock types (Barnett, 1984, 1989; McGuire and Williams, 1998). Few studies have examined the effects of seedling size, per se, on field performance. Barnett (1984) reported that seedling size (e.g. root-collar diameter (RCD), shoot weight, root weight) was related to total sugars (%), reducing sugars (%) and lipids (%) but was not related to either nitrogen concentrations (%) or chlorophyll content (%). RCD (1.9–3.6 mm) was not related to survival (which was excellent) but was positively related to diameter growth during the first 2 years after planting. In a later study, container-grown seedlings with an RCD of 3.7 mm had the same survival (96%) as those with a diameter of 5.5 mm (Barnett, 1991b). Regardless of initial diameter, diameter growth during 17 months after planting in the field was also about the same (9.5–9.7 mm).

One trend that has occurred over the past three decades is that average size of container-grown seedlings has increased. During the 1970s, stock was relatively young (<18 weeks old) and the average RCD ranged from 1.9 to 3.6 mm (Goodwin, 1974; Barnett, 1984, 1989). By 1983, stock size might have ranged from 3 to 5.5 mm (Barnett, 1991b). Some nursery managers now produce container-grown longleaf pine seedlings that average 10–11 mm in RCD (Table 1). Although the size of container stock has been increasing, research to show that seedling diameter is positively related to field performance is lacking. If small container-grown seedlings (e.g. RCD = 4 mm) survive and grow as well as larger stock (e.g. RCD = 9 mm), then nursery costs could be reduced without lowering field performance. Although there are many reports of field performance of container-grown seedlings, only a few researchers have reported the initial RCD of seedlings (Table 1).

The main objective of this study was to examine seedling quality factors related to the performance of container-grown longleaf pine. Hypotheses tested for longleaf pine were: (i) container type does not affect initial survival; (ii) container type does not affect early growth; (iii) container type does not affect root-growth potential; (iv) the RCD of container-grown seedlings does not affect initial survival; (v) the RCD of container-grown seedlings does not affect early growth; (vi) groundline diameter (GLD) is not related to emergence from the grass stage; (vii) there are no site by treatment interactions; (viii) nursery spacing had no effect on seedling performance; and (ix) previous site conditions do not affect initial survival.

2. Materials and methods

2.1. Nursery culture

Longleaf pine seedlings from a southern Mississippi seed source were grown in six container types at the USDA Southern Forest Experiment Station research nursery in Pineville, Louisiana (31°19′N, 92°26′W). Container types included styroblock® (Beaver Plastics, Edmonton, Alta, Canada), Multipot® (Stuewe & Sons, Inc., Corvallis, OR), Hiko® (BBC AB, Profilgatan 15, Landskrona, Sweden) and Jiffy® (Jiffy Products of America, Inc., Norwalk, OH). The styroblock® tray was model 112/95 (112 cells per block and 95 cm^3/cell) and the cell walls were treated with SpinOut® (Griffin LLC, Valdosta, GA). The treatment code for this container type is Cu (Table 2). Although two types of Multipot® trays were used (M3 and M6), the cavity size (98 cm^3) was the same for both containers. The difference was in number of cavities per m^2 (441 for M3 versus 581 for M6). The Hiko® tray (H) had the widest cell diameter of any container type. The two Jiffy® pellets included short (JPs) and standard (JP) versions.

Containers were filled with a peat:vermiculite (1:1, v/v) medium that contained a slow-release fertilizer (Osmocote® 18-6-12; Scotts Company, Marysville, OH) at a rate of 3.56 kg/m^3. Seeds were sown on 24 April 2000 and seedlings were grown using procedures described by Barnett and McGilvray (1997). The containers were covered with a 10% shade cloth until seed germination was complete. About 3 weeks after sowing, the shade cloth was removed and seedlings were exposed to full sunlight. All of the

Table 2
Dimensions of containers used to produce *P. palustris* seedlings

Code	Stock	Model	Cavity depth (cm)	Cavity diameter (cm)	Cavity volume (cm^3)	Cavities per m^2
Cu	Styroblock+ copper	415B	14.9	3.5	93	530
M3	Multipot-441	#3–96	12	3.8	98	441
M6	Multipot-581	#6–45	12	3.8	98	581
H	Hiko	V-93	8.6	4.1	93	526
JPs	Jiffy Pellet-short	30 mm	6.5	3.3	60	735
JP	Jiffy Pellet	36 mm super	10	3.8	120	588

containers received thiophanate-methyl and metalaxyl fungicides on an approximate 2-week interval during the growing phase. Times of fungicide application varied due to rainfall that delayed treatment. Irrigation was applied during dry periods to prevent medium from drying out. Seedlings were given additional applications of a water-soluble fertilizer (Peters Professional 20-19-18, Water Soluble Fertilizer, Scotts Company, Marysville, OH) late in the growing period to green-up the seedlings. Seedlings were extracted from containers on 6 November, cull or diseased seedlings were removed, and plantable seedlings were packed in boxes and placed in a cooler at 2 °C.

Bare-root seedlings (1 + 0) were grown at the Joshua Timberlands Nursery in Elberta, Alabama (30°27′N, 87°32′W). The soil is a Eustis series and is classified as a siliceous, thermic psammentic paleudult. Seed from a seed orchard in Mississippi were sown in March 2000 and seedlings were grown at a density of 129 m^{-2}. During the growing season, seedlings were fertilized with ammonium nitrate (448 kg ha^{-1}), potassium nitrate (112 kg ha^{-1}) and potassium chloride (56 kg ha^{-1}). Needles were clipped on 14 July, 15 August and 14 September. Roots were undercut on 15 October and lateral root pruning was conducted on 15 November. Seedlings were lifted by hand and roots were sprayed with a water-absorbent gel. Seedlings were placed in bags and transported to Auburn University for storage in a cooler.

2.2. Root growth potential

A root growth potential (RGP) study was initiated in January in a greenhouse at Auburn University's Pesticide Research facility. Five aquariums (37.8 l per aquarium) equipped with aerators were double wrapped with black plastic and filled with tap water. Plywood tops with 30 drilled holes about 2.5 cm in diameter were placed on the top of the aquariums. New, white root growth was removed from the bare-root seedlings and from the outer edges of the root plugs for container-grown seedlings. Initial root-collar diameters (RCD) were measured and recorded. Each aquarium served as a replication and each contained four seedlings from each of the seven treatments (28 seedlings per aquarium). Each seedling was placed in a hole in the plywood at random and the root plugs were suspended in the water below the plywood top. Water temperature and air temperatures were recorded weekly during the study to ascertain laboratory growing conditions. Low temperatures were observed around 23:00 h and high temperatures were observed around 13:00 h. Seedlings were allowed to grow in the aquariums for 5 weeks.

Root emergence from three plug zones (Zone A: top half of plug, Zone B: bottom half of plug, and Zone C: bottom portion of plug) was recorded for each seedling. Similar zones for bare-root seedlings were based on the length of the taproot. After 5 weeks, all new roots were excised and dried at 65 °C for 36 h, and then weighed.

One shoot from each treatment was systematically sampled from one replicate and subjected to inductively coupled argon plasma (ICAP) analyses at the Auburn University Soil and Foliage testing lab. Total N concentration in the foliage was determined by the combustion method (Matejovic, 1995).

2.3. Field studies

At Auburn, seedlings were removed from cool storage and each seedling was tagged as to container type and its RCD was recorded. Seedlings were grouped according to planting location, bagged, and returned to cool storage. Between 4 December 2000 and 15 January 2001, seedlings were transported to field sites and planted by hand. Augers were used to plant container stock and shovels were used to plant bare-root stock. Studies were installed at four sites across east central and southern Alabama. Each site was divided into two study areas. A complete main test contained 180 single-tree plots for each treatment (arranged in 15 or 18 rows of 10 single-tree plots per treatment per row). A separate small study was installed for destructive sampling. The destructive study contained five rows of two single-tree plots per treatment per row.

2.3.1. Macon county site

This site was a recently abandoned agricultural field in Macon County near Society Hill, Alabama (32°26′N, 85°28′W). It consisted of approximately 0.34 ha of Gilead sandy loam (80% sand, 17.5% silt, and 2.5% clay) with less than 5° of slope. Chemical site preparation was applied using a broadcast application of glyphosate and metsulfuron. Due to area constraints, seedlings were planted in December on a 1.0 m × 2.0 m spacing. On 18 April 2001, weeds were treated with an over-the-top application of oxyfluorfen (0.45 kg active ingredient per hectare). On 29 May, weeds were treated with an over-the-top application of oxyfluorfen and prodiamine (0.45 and 0.73 kg active ingredient per hectare, respectively). Additional spot applications of 2% glyphosate were applied on 25 June (with a wiper) and on 9 July 2001 rows were sprayed with a 1% solution of glyphosate.

2.3.2. Lee county site

This site was a recently clear-cut pine forested area owned by MeadWestvaco Corporation near Pine Grove, Alabama (32°43′N, 85°15′W). Soils were classified as a Pacolet sandy loam with a surface soil texture of 64% sand, 29% silt, and 7% clay. Approximately 1.61 ha with less than 7° of slope was bedded 16 weeks prior to planting. Seedlings were planted in January on a 2.7 m × 4.0 m spacing. On 29 May 2001, weeds were treated with an over-the-top application of oxyfluorfen and prodiamine (0.45 and 0.73 kg active ingredient per hectare, respectively). Weeds were treated on 25 June with a weed wipe treatment of 2% glyphosate.

2.3.3. Covington county site

This site was a recently abandoned agricultural field near Rome, Alabama (31°09′N, 86°40′W) and consisted of a Dothan and Malbis sandy loam soil. Texture analysis showed 81% sand, 16% silt, and 3% clay for the top 26 cm of soil. The study site was approximately 1.21 ha in size and exhibited less than 5° of slope. The site (previously under corn (*Zea maize* L.)/peanut (*Arachis hypogaea* L.) farming production) was scalped and ripped prior to planting in January on a 2.0 m × 3.3 m spacing. Due to a limited supply of JPs stock, 13 single-tree plots in the main test did not receive this container type. Weeds were treated on 18 June 2001 with an over-the-top treatment of oxyfluorfen and prodiamine (0.45 and 0.73 kg active ingredient per hectare, respectively) and again on 29 June with a weed wipe treatment of 2% glyphosate. On 20 July, weeds between the rows were treated with a 1% solution of glyphosate.

2.3.4. Escambia county site

This site was a cutover upland mixed pine and hardwood stand located on Dixon Family Partnership land adjacent to Auburn University's Solon Dixon Forestry Education Center near Dixie, Alabama (31°10′N, 86°41′W). Site preparation included a broadcast application of imazapyr and glyphosate followed by a prescribed burn in late summer of 2000. The study area was approximately 1.01 ha in size and was located on a transition zone between an Orangeburg sandy loam and a Dothan and Malbis sandy loam soil. The slope was less than 10° and the topsoil was classified as a sand (90% sand, 10% silt, and 0% clay). Container and bare-root seedlings were planted at the same time in January 2001 on a 1.7 m × 3.3 m spacing. Due to a lack of seedlings, JPs stock was not planted on this site and only nine rows contained JP stock. No herbicides were applied after planting.

2.4. Destructive sampling

At each site, five seedlings from each treatment were selected randomly (using a table of random numbers) and were excavated according to methods developed by the USDA Soil Dynamics Laboratory at Auburn, Alabama. A steel tube (24.5 cm diameter × 60 cm deep) was centered around the seedling and was driven into the ground using a hydraulic cylinder mounted on the front of a tractor. Once the tube had been driven approximately 51 cm into the ground, the driving head was removed and the hydraulic cylinder was connected to a chain attached to a collar located just below a small outer lip of the core tube. The hydraulic cylinder was then used to lift the tube containing the seedling and soil core. In order to excavate five samples of JPs stock at the Covington and JP stock at the Escambia County site, seedlings were randomly selected from the main test plots. These trees were not included in the second-year data.

Following excavation, GLD was measured and the seedlings were carefully removed from the soil cores. For each seedling, the main geotropic root was examined to determine if it was part of the original taproot or had developed as an adventitious root at the end of the original taproot. Adventitious roots just above the point of air-pruning (for container stock) of the taproot or undercutting (for bare-root stock) of the taproot were classified as Type A sinker roots (South et al., 2001). Primary lateral roots that had developed geotropic growth were classified as Type B sinker roots (http://nativeplants.for.uidaho.edu/uploads/2-2NPJ126-130.pdf). The number of Type A and Type B sinker roots was recorded for each seedling.

Harvested seedlings were placed in numbered bags and returned to Auburn for further analysis. In the laboratory, all roots outside of the original plug were clipped and rinsed clean of any remaining soil. Root dry weights (RDW) were determined using standard drying ovens for 36 h at 65 °C. All green needles were removed from the stems and were oven-dried. Needles were delivered to the Auburn University Soil and Foliage Testing Laboratory for determination of needle dry weight and total nitrogen concentration.

2.5. Statistical analysis

Analyses were carried out using the Statistical Analysis System (SAS Institute, Inc., 1989). Contrast statements were used under the general linear model procedure. Analysis of variance for a randomized complete block design was conducted for each of the field studies. After verifying site by treatment interactions, each study was analyzed separately. Nutrient samples were analyzed as a completely randomized study. Plot means were used as observations and contrast statements were considered significant at an alpha level of 0.05. Five contrast statements were used to compare treatments at the Escambia site while six contrasts were used for the remaining sites.

To determine the relationship between seedling diameter and field performance, container seedlings were grouped into six initial GLD classes (4.5–5.49, 5.5–6.49, 6.5–7.49, 7.5–8.49, 8.5–9.49, and 9.5–10.49 mm). To determine the effect of seedling diameter on emergence from the grass stage, container seedlings were divided into two groups (>23 and <23 mm) according to second-year GLD. A root bound index (RBI) was calculated for each container seedling by dividing the root-collar diameter (RCD) by the cell cavity diameter (Table 2). Relative growth rates were not used to compare stock types because this method of analyses indicates a small seedling will a have higher mean relative growth rate than a large seedling when both are growing according to the same growth curve (South, 1991).

3. Results

3.1. Root growth potential

Low and high air temperatures in the greenhouse averaged 18 and 24 °C, respectively. Water temperatures averaged 19 °C (low) and 20 °C (high). There was a large difference in RGP between bare-root and container-grown seedlings (Table 3). Overall, container seedlings averaged 5.5 new roots per seedling while bare-root seedlings averaged 1.7 new roots per seedling. Several bare-root seedlings produced no new roots. Among the container types, seedlings with the copper treatment (Cu) had more new roots than the JPs or H seedlings. Bare-root stock, and stock grown in JP and JPs containers were lower in root dry weight than seedlings grown in the other container types. The Cu seedlings expressed the greatest root dry weight. The location of the emerged new roots differed among container types. Seedlings with the most new roots in the upper half of the plug were the Cu seedlings and the JP seedlings. Container types with less than 1.5 new roots emerging from the bottom of the container plug included Cu, JP, and JPs. Overall, there was a

Table 3
Root growth potential (RGP) of *P. palustris* seedlings (error d.f. = 24)

Code	Stock	RCD (mm)	RGP (#)			
			Total	Zone A upper half	Zone B lower half	Zone C
Cu	Styroblock+ copper	7.3	7.90	2.95	2.35	2.60
M3	Multipot-441	7.4	7.10	0.75	2.25	4.10
M6	Multipot-581	7.0	4.60	0.60	0.60	3.40
H	Hiko	6.5	4.00	0.50	0.85	2.65
JPs	Jiffy Pellet-short	6.8	2.45	0.87	1.40	0.92
JP	Jiffy Pellet	7.0	6.75	2.83	3.20	1.43
BR	Bare-root	13.6	1.70	0.00	0.85	0.85
	Significant contrasts	1, 2	1, 2, 4, 5, 6	1, 2, 4, 5	2, 4, 5, 6	1, 3
	Coefficient of variation	6.8	36.5	55.5	53.2	67.2

Contrasts: (1) BR vs. Cu + M3 + M6 + H; (2) BR vs. JPs + JP; (3) Cu + M3 + M6 + H vs. JPs + JP; (4) Cu vs. M3 + M6 + H; (5) JPs vs. JP; (6) M3 vs. M6.

positive relationship between initial RCD of container seedlings and RGP (Fig. 2).

3.2. Nutrient concentration

Foliar analysis revealed bare-root seedlings contained higher foliar concentrations of N at time of planting than did container stock (Table 4). In addition, concentrations of Cu and Mo in bare-root seedlings (Table 5) were higher than for container types combined (contrast test: $P > F = 0.002$ and 0.035, respectively). In contrast, bare-root stock had lower Zn concentrations (contrast test: $P > F = 0.027$) and had lower B concentrations than JP + JPs stock (contrast test: $P > F = 0.029$). Seedlings grown in the JP and JPs container types tended to have higher concentrations of P, Ba, Zn, and Na than seedlings grown in other containers. Among all treatments, there were no significant contrasts for foliar concentration for Ca (0.179%), K (0.755%), Mg (0.121%), Fe (96 ppm), Mn (121 ppm), Al (146 ppm), Co (0.131 ppm), Cr (2.4 ppm), and Pb (1.8 ppm). A year after planting, there was no significant treatment effect on foliar nitrogen concentration (Table 4).

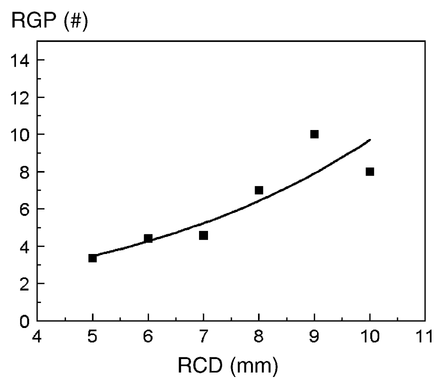

Fig. 2. Effect of root-collar diameter (RCD) on root growth potential of container-grown *P. palustris* seedlings. Each point represents the mean for eight or more container seedlings.

3.3. Survival

There was an interaction between site and planting stock ($P > F = 0.0001$) because survival rankings varied by site (Table 6). Overall, survival after the first year was not significantly different between old-field and cutover sites ($P > F = 0.442$). However, by the second year, overall survival of five container types (Cu, M3, M6, H, JP) was higher ($P > F = 0.0001$) for the two cutover sites (81.6%) than for the two old-field sites (65.7%). Overall second-year survival was greater than 85% at the Escambia site where no significant differences among planting stocks were detected ($P > F = 0.815$). Planting stock affected survival at the three remaining sites ($P > F \leq 0.0017$). 0.0017). The survival of bare-root seedlings was greater than all six container types at the Covington site and was better than four container types at the Lee site. At the Macon site, there was no significant difference between bare-root and container types. For all sites, the lowest survival occurred with either the JP or JPs seedlings. There were no significant differences in survival among Cu, M3, M6, and H container types.

Table 4
Foliar nitrogen concentration (%) before planting and 1 year after planting *P. palustris* on four sites in Alabama

Code	Stock	Before planting	Covington 1-year	Escambia 1-year	Lee 1-year	Macon 1-year
Cu	Styroblock+ copper	0.6	1.1	1.5	1.4	1.3
M3	Multipot-441	0.7	1.2	1.3	1.3	1.4
M6	Multipot-581	0.8	1.1	1.3	1.4	1.7
H	Hiko	0.7	1.2	1.5	1.3	1.3
JPs	Jiffy Pellet-short	0.7	1.2	–	1.4	1.4
JP	Jiffy Pellet	0.5	1.6	1.4	1.5	1.3
BR	Bare-root	1.3	1.4	1.3	1.3	1.3
	Significant contrasts	1, 2	1, 3, 5	4	–	–
	Coefficient of variation	16.7	12.0	10.9	13.7	16.6
	Error degrees of freedom	23	28	24	28	28

Contrasts: (1) BR vs. Cu + M3 + M6 + H; (2) BR vs. JPs + JP; (3) Cu + M3 + M6 + H vs. JPs + JP; (4) Cu vs. M3 + M6 + H; (5) JPs vs. JP; (6) M3 vs. M6 (for Escambia: (2) BR vs. JP; (3) Cu + M3 + M6 + H vs. JP; (5) not applicable).

For both container stock and bare-root stock, there was a relationship between RCD and seedling survival (Fig. 3). For bare-root stock, survival increased from 8 to 12 mm RCD. For container stock, survival was optimum when RCD was 9 mm. There was a strong relationship between seedling survival and RBI. Survival was good when RBI was less than 28% but was low if the RBI was greater than 30% (Fig. 4).

3.4. Morphological variable

There were significant site by treatment interactions for both second-year height and diameter ($P > F \leq 0.0001$). In general, height growth was greater for bare-root stock than for container stock (Fig. 5). At planting, the bare-root stock was 4–5 mm larger than that of container stock (Table 7) and after 1 year, this difference was 4–10 mm. Two years after planting, the difference had expanded to 13–18 mm at the Covington site while at the Macon site, some container types were only 2 mm smaller than bare-root stock (Table 6).

There was a strong relationship between second-year GLD and emergence from the grass stage ($P > F = 0.0001$). Of the container seedlings with second-year GLD greater than 23 mm, 96.6% had emerged from the grass stage. In contrast, only 2.7% of seedlings with GLD $\leq$ 23 mm had begun to elongate. Bare-root and container seedlings emerged from the ‘‘grass’’ stage at about the same time at the Escambia and Macon sites. In contrast, bare-root seedlings initiated height growth first at the Covington and Lee County sites. As a result, average height of bare-root stock on these sites was 15–41 cm taller than

Table 5
Concentrations of phosphorus, copper, zinc, boron, barium, sodium, and molybdenum in the foliage of *P. palustris* seedlings before planting (error d.f. = 24)

Code	Stock	P (g/kg)	Cu (mg/kg)	Zn (mg/kg)	B (mg/kg)	Ba (mg/kg)	Na (mg/kg)	Mo (mg/kg)
Cu	Styroblock+ copper	0.86	2.5	76	18	2.5	176	0.00
M3	Multipot-441	1.14	1.0	115	29	4.4	242	0.16
M6	Multipot-581	1.96	0.5	108	26	3.1	211	0.04
H	Hiko	1.10	0.4	75	20	2.4	207	0.00
JPs	Jiffy Pellet-short	1.58	0.4	181	30	5.3	642	0.08
JP	Jiffy Pellet	1.30	1.6	160	26	4.4	373	0.24
BR	Bare-root	1.08	3.2	50	16	3.0	221	0.24
	Significant contrasts	3	1, 2, 4	2, 3	2	2, 3	2, 3, 5	1
	Coefficient of variation	33.1	92.4	56.1	40.7	36.3	56.7	131.0

Contrasts: (1) BR vs. Cu + M3 + M6 + H; (2) BR vs. JPs + JP; (3) Cu + M3 + M6 + H vs. JPs + JP; (4) Cu vs. M3 + M6 + H; (5) JPs vs. JP; (6) M3 vs. M6.

Table 6
Survival, groundline diameter (GLD), height, and seedlings out of grass stage (%) 2 years after planting *P. palustris* on four sites in Alabama

Stock	Covington	Escambia	Lee	Macon
Survival (%)				
Cu	69.3	87.8	84.2	70.6
M3	67.3	83.9	71.7	67.8
M6	64.4	85.5	73.7	67.8
H	64.0	86.7	84.8	64.4
JPs	43.4	–	49.7	53.9
JP	58.0	82.1	75.0	50.0
BR	89.3	85.0	93.8	66.7
Significant contrasts	1, 2, 3, 5	–	1, 2, 3, 5	2, 3
Coefficient of variation	27.4	13.7	21.3	27.0
Error degrees of freedom	89	76	102	102
GLD (mm)				
Cu	20.7	34.6	44.3	47.4
M3	23.3	33.6	49.1	47.7
M6	20.6	34.1	45.9	44.7
H	20.0	33.2	46.9	46.9
JPs	18.1	–	45.1	45.2
JP	20.3	34.3	43.0	42.2
BR	36.3	46.0	53.7	49.6
Significant contrasts	1, 2, 3, 5, 6	1, 2	1, 2, 3, 4, 6	1, 2, 3, 5, 6
Coefficient of variation	6.3	8.5	7.8	8.3
Height (cm)				
Cu	4	29	29	29
M3	6	26	35	36
M6	4	26	28	27
H	3	26	26	30
JPs	2	–	18	25
JP	3	25	17	19
BR	26	70	50	51
Significant contrasts	1, 2, 3	1, 2	1, 2, 3, 6	1, 2, 3, 5, 6
Coefficient of variation	55.8	23.5	24.2	29.3
Out of grass stage (%)				
Cu	24	81	81	66
M3	20	77	70	63
M6	23	78	66	62
H	19	79	79	62
JPs	10	–	40	48
JP	13	80	61	43
BR	83	83	90	63
Significant contrasts	1, 2, 3	–	1, 2, 3, 4, 5	2, 3
Coefficient of variation	48	16.4	22.7	29.7

Contrasts: (1) BR vs. Cu + M3 + M6 + H; (2) BR vs. JPs + JP; (3) Cu + M3 + M6 + H vs. JPs + JP; (4) Cu vs. M3+M6+H; (5) JPs vs. JP; (6) M3 vs. M6 (for Escambia: (2) BR vs. JP; (3) Cu + M3 + M6 + H vs. JP; (5) not applicable).

the next tallest container type. Growth of both bare-root and container stock appears to be positively related to RCD at planting (Fig. 5).

One year after planting, bare-root seedlings had more needle mass than any of the container types (Table 7). The root structure differed among treatments (data not shown). Only 3% of excavated seedlings had what appeared to be an original taproot and there were no differences among treatments ($P > F = 0.479$). On average, there were about 2.8 sinker roots per excavated seedling and there were no significant differences among treatments for either

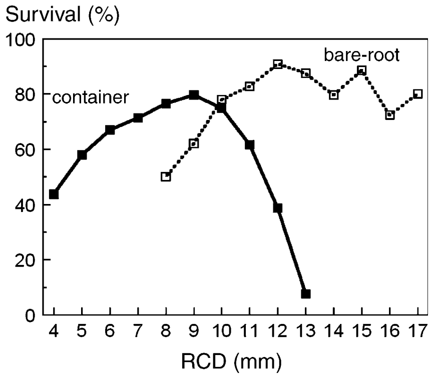

Fig. 3. Effect of root-collar diameter (RCD) at planting on second-year survival of container-grown and bare-root *P. palustris* seedlings. Each point represents the mean of 13 or more seedlings.

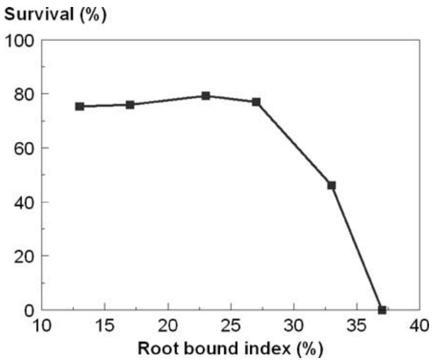

Fig. 4. Effect of root bound index (RCD/cell diameter) on second-year survival of container-grown *P. palustris* seedlings (all sites combined). Each point represents the mean of 13 or more seedlings.

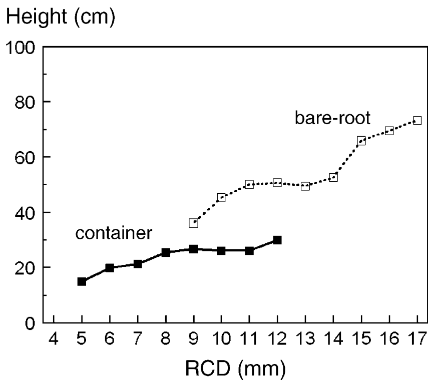

Fig. 5. Effect of root-collar diameter (RCD) on second-year height of *P. palustris* seedlings (all sites combined). Each point represents the mean of 12 or more seedlings.

Type A or Type B sinker roots ($P > F > 0.44$). Overall, there were about 1.8 Type A sinker roots per seedling.

4. Discussion

4.1. Container seedlings

Container type does affect survival and early growth of longleaf pine. However, this effect appears to be more related to RCD, RGP, and container depth than it does with root form, per se. RGP was related to seedling size (RCD) and the container type with the lowest RGP was the smaller mesh-covered plug (JPs) while the greatest RGP was the copper-treated styroblock (Cu). Regardless of container type, seedlings with RCD less than 5.5 mm did not survive as well as seedlings with RCD between 5.5 and 10.5 mm (Fig. 3). Height growth was positively related to initial RCD. There was a 1.8 cm increase in second-year height for every 1 mm increase in RCD.

There were site by treatment interactions for survival, height, GLD, and emergence from the grass stage. On the easy-to-regenerate cutover site in Escambia county, container type did not affect either survival or early growth. However, on the remaining three sites, seedlings grown in the mesh-covered plugs (JP and JPs) did not perform as well as seedlings grown in the other containers. Although they have fewer roots emerging from the bottom of the plug in the RGP trial (Table 3), and did not have a pronounced ‘‘cage’’ effect, survival and height growth was less on all sites (but the difference at Escambia was not statistically significant).

Some have proposed that field performance declines as the seedlings become larger in the container (Salonius et al., 2000, 2002). Our data support this hypothesis since seedlings with an RBI greater than 27% had lower survival. At this time, we do not feel comfortable proposing an underlying mechanism to explain why high RBI values result in low survival. Although RGP tends to increase with increasing size (Fig. 2), we did not test the RGP of seedlings with high RBI values. For the RGP study, mean RBI values ranged from 16 (H) to 21 (Cu and JPs). Barnett (1991b) obtained high survival of longleaf pine seedlings when they had RBI values

Table 7
Initial groundline diameter, first-year GLD, foliage weight, and stem plus root dry weight 1 year after planting *P. palustris* on four sites in Alabama

Stock	Covington	Escambia	Lee	Macon
Initial groundline diameter (mm)				
Cu	9.0	8.8	8.2	8.7
M3	8.8	8.6	8.4	8.5
M6	9.0	8.5	7.9	8.8
H	7.9	8.0	7.4	7.9
JPs	7.7	–	7.0	7.5
JP	8.1	8.1	7.6	8.1
BR	12.4	12.8	12.1	12.9
Significant contrasts	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3, 5, 6	1, 2, 3, 4, 5
Coefficient of variation	6.0	6.3	6.1	5.8
Error degrees of freedom	96	72	96	96
First-year groundline diameter (mm)				
Cu	11.4	20.8	15.3	16.1
M3	12.2	19.8	16.6	16.6
M6	11.6	19.3	15.1	15.2
H	9.8	19.8	14.8	15.4
JPs	9.5	–	12.6	14.0
JP	10.1	18.6	13.0	12.8
BR	20.2	26.8	20.8	21.1
Significant contrasts	1, 2, 3	1, 2, 3, 4	1, 2, 3, 6	1, 2, 3, 5, 6
Coefficient of variation	11.5	6.8	7.9	8.2
Error degrees of freedom	84	72	96	96
Foliage dry weight (g)				
Cu	30	70	37	32
M3	28	48	39	39
M6	30	39	32	37
H	29	39	33	38
JPs	25	–	29	27
JP	27	37	28	30
BR	42	94	60	64
Significant contrasts	1, 2	1, 2, 4	1, 2	1, 2, 3
Coefficient of variation	22.7	44.3	31.3	20.4
Error degrees of freedom	28	24	28	28
Stem plus root dry weight (g)				
Cu	4.1	20.2	14.0	5.4
M3	4.0	13.5	15.1	10.6
M6	4.2	7.5	11.2	10.9
H	3.7	11.5	13.8	8.1
JPs	2.9	–	6.5	4.4
JP	3.7	8.4	7.6	4.1
BR	5.9	14.5	23.3	18.5
Significant contrasts	–	4	1, 2, 3	1, 2, 3
Coefficient of variation	68.6	65.1	58.1	59.2
Error degrees of freedom	28	24	27	28

Contrasts: (1) BR vs. Cu + M3 + M6 + H; (2) BR vs. JPs + JP; (3) Cu + M3 + M6 + H vs. JPs + JP; (4) Cu vs. M3 + M6 + H; (5) JPs vs. JP; (6) M3 vs. M6 (for Escambia: (2) BR vs. JP; (3) Cu + M3 + M6 + H vs. JP; (5) not applicable).

ranging from 10 to 15 and were outplanted in September. Future studies with container-grown longleaf pine should include RBI to determine if a similar relationship to Fig. 4 can be repeated.

If seedlings with RBI values greater than 27% survive, it appears that early growth is not affected. Seedlings with an RBI of 33 averaged 27.9 cm tall after 2 years in the field. Although future growth might be affected, at this time there appears to be no evidence of a relationship between RBI and early height growth.

Numerous reports have been made on the effects of treating containers with copper to prevent conifer lateral roots from bending downwards and forming a ''cage'' effect (Romero et al., 1986; Ruehle, 1985; McDonald et al., 1984). However, a previous study with a SpinOut® treatment found that shoot weight of longleaf pine increased by 28% and plugs were easier to extract (Barnett and McGilvray, 2002). In the present study, the Cu treatment increased RGP when compared with the hardwall containers. The elimination of the ''cage'' effect resulted in an increase in the number of new roots emerging from the sides of the plug (Table 3). However, the increase in RGP was not reflected in either greater survival or greater height after 2 years (Table 6).

The effect of seedling spacing can affect the performance of both bare-root (Hatchell and Muse, 1990; Barnett, 1991a) and container seedlings (Table 6). The performance of Multipot® containers was greater when seedlings were grown at a density of 441 m^{-2} versus the higher density of 581 m^{-2}. Seedlings at the lower density had greater RGP and greater diameter after 2 years than seedlings at the higher density. Since the container volume was the same, the increase in diameter and height growth is likely a result of more light available per seedling.

Previous site history appears to have an influence on seedling survival of container-grown longleaf pine. For some time, field foresters have noted lower survival on old-field sites than on adjacent cutover sites. Old-field sites may have pest problems that are not typically associated with cutover sites. For example, on some sites in northern Florida, scraping away the topsoil increased survival by 10–40% points on pest-infested agricultural soils (Barnard et al., 1995). In our study, survival of JP stock was 75–82% on the two cutover sites and was less than 54% survival on the agricultural soils.

4.2. Bare-root seedlings

Early field performance of bare-root longleaf pine is positively related to seedling size (White, 1981; Lauer, 1987; Hatchell and Muse, 1990; Barnett, 1991a). The sooner seedlings reach a GLD of 23 mm, the sooner they emerge from the grass stage. However, in many outplanting studies (e.g. Table 1), the average RCD of longleaf pine at time of planting was not recorded. Therefore, for most studies, it is not clear if bare-root seedlings were larger, smaller, or had the same RCD as container-grown seedlings. What is known is that container-grown seedlings typically survive better than bare-root stock (Fig. 1). When comparing seedlings with the same RCD (7.5–9.5 mm), we also found that container seedlings had about 20% better survival than bare-root stock (Fig. 3). It is likely that when longleaf pine was grown in the nursery at densities of 190–325 m^{-2}, many bare-root seedlings had RCD of 7.5–9.5 mm at time of lifting (Hatchell and Muse, 1990; Barnett, 1991a). Growing bare-root seedlings at high seedbed densities might explain why survival of bare-root seedlings in some studies was lower than container-grown seedlings. Prior to 2003, researchers conducting stock-type trials rarely report the RCD of bare-root longleaf pine seedlings (Table 1). In our study, bare-root seedlings grown at 129 m^{-2} (average RCD = 12.5 mm) were larger than container-grown seedlings (average RCD = 8.2 mm) and second-year survival of bare-root seedlings was 9% points greater than container stock. We recommend that RCD be reported in future studies so that researchers might gain a better understanding of reasons why container stock survives better than bare-root stock.

However, we are not certain about an explanation for the better performance of bare-root stock in this study. Confounding factors between bare-root and container types not only include differences in initial size, but also include differences in genetics, planting method, nursery practices (e.g. fertilization, irrigation, top-clipping, seedlings spacing, lifting date, etc.), planting date, and weather. For example, a −10 °C freeze occurred on 21 December 2000 after container seedlings had been planted at the Lee and Macon sites but at this time bare-root stock was still in storage.

Another possible explanation for higher survival might be related to seedling nitrogen status. Regardless of planting stock, nitrogen levels in longleaf pine can be less than 0.9% in the winter (Rodríguez-Trejo and Duryea, 2003). Nursery managers typically withhold nitrogen fertilizers to avoid producing pot-bound seedlings. At some nurseries, container-grown longleaf pine seedlings might receive only 38 kg N ha^{-1} (Rodríguez-Trejo et al., 2003). In our study, bare-root seedlings received 164 kg N ha^{-1} and their nitrogen status at time of planting (1.3% N) was the same as that noted a year after planting. However, a year after planting at the Covington site, hardwall container stock was still lower in foliar nitrogen than bare-root stock (Table 4). During the spring of 2001, the needles of bare-root seedlings were noticeably greener than container stock.

We observed that bare-root longleaf pine seedlings rarely have the original taproot elongate after planting. Instead, ‘‘type A’’ sinker roots form just above the point where the taproot was undercut. In most cases, two ‘‘type A’’ sinkers took over the role of the taproot. In addition, about one lateral root turned into a sinker root (a type ‘‘B’’ sinker root). None of the bare-root taproots we excavated appeared to have a sinker root that formed from the original taproot (i.e. no adventitious sinker roots would be formed). From this study, it appears that sinker root development is similar for both bare-root stock and air-pruned container-grown stock (South et al., 2001).

Only a few RGP studies have been conducted with longleaf pine. One study found 39 new roots per seedling for freshly lifted trees and 10 new roots for seedlings stored for 3 weeks (South and Loewenstein, 1994). Another test also reported 39 new roots but 31% of the bare-root seedlings exhibited no new roots (McGuire and Williams, 1998). We also report no new roots for 17 out of 20 bare-root seedlings tested. Despite this high percentage of seedlings with no new roots, field survival of bare-root seedlings was greater than 80%.

5. Conclusions

On easy-to-regenerate sites, container type may not affect seedling survival (assuming the RBI is less than 27% and the RCD is greater than 7 mm). However, on difficult-to-regenerate sites, container type can affect both survival and early growth. Treating container walls with a copper solution or growing seedlings at a wider spacing can increase the root-growth potential of longleaf pine. For container-grown stock, RCD appears to be related to both seedling survival and RGP. It appears that previous site conditions can affect seedling performance since old-field sites tend to have lower survival than cutover sites. RCD can be related to seedling survival. Height growth of longleaf pine appears to be related to stock size regardless of the ease of establishment. Regardless of site, emergence from the grass stage is strongly related to the groundline diameter of seedlings. From this study, it appears that seedling quality can decline if seedling size becomes too large for the container.

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