Growing *Pinus nigra* Seedlings in Spinout™-Treated Containers Reduces Root Malformation and Increases Growth After Transplanting[1]

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Abstract

Root malformation originating during container production causes mechanical instability and plant mortality when those seedlings are transplanted. We investigated the effects of chemical (interior container surfaces treated with Spinout™ or not) or mechanical container modifications (vertical slits or no vertical slits), and the effects of substrate bulk density on the growth of *Pinus nigra* (Arnold) seedlings during plug production and after transplanting. Seedlings grown in compacted substrate had the greatest shoot, root and total plant dry weights five months after seeding in plug trays. However the incidence of root malformation was also greatest when seedlings were grown in compacted substrate. Unless root pruned, root malformations were retained after transplanting. Seedlings with unpruned roots grown in Spinout™-treated containers had higher regenerated root dry weight than those grown in untreated containers four months after transplanting. Root pruning before transplanting reduced growth of the seedlings regardless of container configuration and of substrate bulk density. Root regrowth and seedling quality after transplanting were greatest for seedlings grown in the treatment combination of no Spinout™, compacted substrate and no slits. Seedlings produced under natural photoperiods formed a resting bud when the seedlings were approximately 2.5 cm (1 in) tall in spring season. Within two weeks shoot elongation resumed, which resulted in branched seedlings. Root malformation can be induced during plug production and is retained after transplanting unless corrected by root pruning.

Index words: Austrian Pine, container production, substrate compaction, mechanical container modification, transplanting, regrowth potential, copper hydroxide.

Significance to the Nursery Industry

Long-term performance of nursery stock in the landscape is affected by nursery production techniques. Planting stock with root malformations induced during container production can increase mortality and mechanical instability when planted in the landscape. In this study, we examined treatments that may minimize root malformation. *Pinus nigra* seedling dry weight was increased when produced in substrate bulk densities from 0.71 to 1.01 g cm^{-3}. However, the percentage of seedlings with root malformation was higher at those bulk densities than when seedlings were produced at lower substrate bulk densities. For *P. nigra*, root malformation can be corrected by pruning roots above the point of root deflection; however, growth after transplanting is reduced compared with non-root pruned seedlings produced under similar conditions. Producing *P. nigra* seedlings in Spinout™-treated 51 cell plug trays for five months resulted in smaller seedlings than those produced in untreated containers. However, Spinout™-produced seedlings needed less root pruning to correct root malformations, resulting in greater root growth four months after transplanting.

Introduction

Containerized pine seedling production has many benefits compared to bare-root production, including faster growth and extended planting season. However, container-grown stock is subject to root malformation and establishment can be compromised. Root malformation affects the stability and growth of trees (3). An increase in root deformation resulted in decreased stability of outplanted *Pinus contorta* seedlings (2). Decreased root growth was caused by decreased translocation capacity (5, 10). Root malformation decreases tensile strength making trees more prone to fungal attacks on both roots and stems (11). Poor root development in plantations established with container-grown conifers was first reported in the late 1970s (11).

Root malformation formed during production is caused by container design. Smooth interior container surfaces cause circling root development. To reduce circling root development, containers with internal vertical ridges were designed. Vertical slits in the sides of containers (11) and chemical treatment to interior container surfaces (9) were later developed to reduce root malformation.

Coating the interior surfaces of plastic containers with copper paint is another way of reducing malformed roots (12). Cupric carbonate applied to the interior surfaces of containers inhibits root elongation and causes higher-order lateral roots to proliferate when first-order lateral root elongation is inhibited (12). Root elongation resumes when seedlings are removed from the containers (1, 7, 8). Commercial use of chemical container treatments to reduce root malformation began in the late 1980s (9).

Container-grown seedlings may have abnormal buttress root development, which compromises mechanical stability (2, 7). Abnormal buttress root development can begin when seedlings are grown in deep cells with narrow diameters. Roots destined to function as buttress roots are deflected downwards by the interior ridges. These container-grown seedlings have their buttress roots clustered at the container base, instead of developing into shallow, horizontally oriented supporting roots. Also, roots dessicate as they elongate through drainage holes. As other downwardly deflected lateral roots reach the opening, they too are 'air-pruned.' The opening soon becomes blocked, resulting in a physical bar-

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rier to any additional root elongation. Roots reaching the container bottom after the physical barrier develops are deflected upward. The result is a ‘U’ shaped root malformation (Fig. 1). We hypothesized that this ‘U’ malformation is enhanced by compaction of medium resulting from stacking filled trays before seeding.

An additional challenge to *P. nigra* seedling production is poor stem form. To reduce production time, pines are seeded during winter in heated greenhouses and grown under 16 hour or longer photoperiods. When grown under extended photoperiod, *P. nigra* seedlings produce a long central leader with a terminal bud and cluster of lateral buds. When outplanted, the terminal bud vigorously flushes, causing a top heavy, leggy seedling. The objectives of this study were to determine the effects of container modifications and substrate compaction on the growth of *P. nigra* seedlings during plug production and after transplanting.

Materials and Methods

Pinus nigra seedling growth was studied under a factorial combination of container modification (control, vertical slits and interior surface Spinout™ coating) and substrate compaction (compacted and uncompacted). The containers used in this study were 51-strip trays (Growing Systems Inc., Milwaukee, WI). The six treatment combinations used were: 1) Spinout™ [Griffin Chemical Corp., Valdosta, GA], uncompacted medium, no slits; 2) Spinout™, compacted medium, no slits; 3) No Spinout™, uncompacted medium, no slits; 4) No Spinout™, compacted medium, no slits; 5) No Spinout™, uncompacted medium, slits; and 6) No Spinout™, compacted medium, slits.

Spinout™ treatments consisted of two coats of Spinout™ applied by hand to the interior container surfaces. Containers with slits were prepared by cutting, with a Dremel™ drill fitted with a circular blade, three equally spaced vertical slits on individual cells, beginning 1 cm (0.4 in) below the upper rim and continuing for 3.5 cm (1.4 in) of each cell. The slits were made to encourage mechanical root pruning.

Planting substrate was a blend of equal parts of vermiculite, peatmoss and perlite (Evergreen Nursery Co. Inc., Sturgeon Bay, WI). Substrate was added to each individual cell; trays were tapped gently and filled to capacity for the uncompacted substrate treatment. For the compacted substrate treatment, approximately twice the volume of substrate was added to each cell, relative to the uncompacted substrate treatment. Substrate was compacted in 1.3 cm (½ in) lifts by pounding a blunt dowel rod onto the substrate surface.

The volume of individual cells was determined by measuring the volume of water added to a cell with a sealed drain hole. Bulk density was determined by dividing the total cell volume per tray by the weight of added substrate. The weight of added substrate was calculated by subtracting the weight of the empty tray from the weight of the filled tray.

Cold-stratified *P. nigra* seeds were obtained from Evergreen Nursery Co, Inc., Sturgeon Bay, WI. Seeds were placed on moist germination paper at room temperature 24C (75F) until germinated during February 2002. Germinated seeds (radicals less than 0.5 cm long [0.2 in]), were sown one seed per cell in dibbled holes, carefully placing seeds so that the radicle was oriented downward. The seeds were covered with loose medium.

Seeded trays were moved in March 2002 to a greenhouse under natural photoperiods. Photosynthetic active radiation

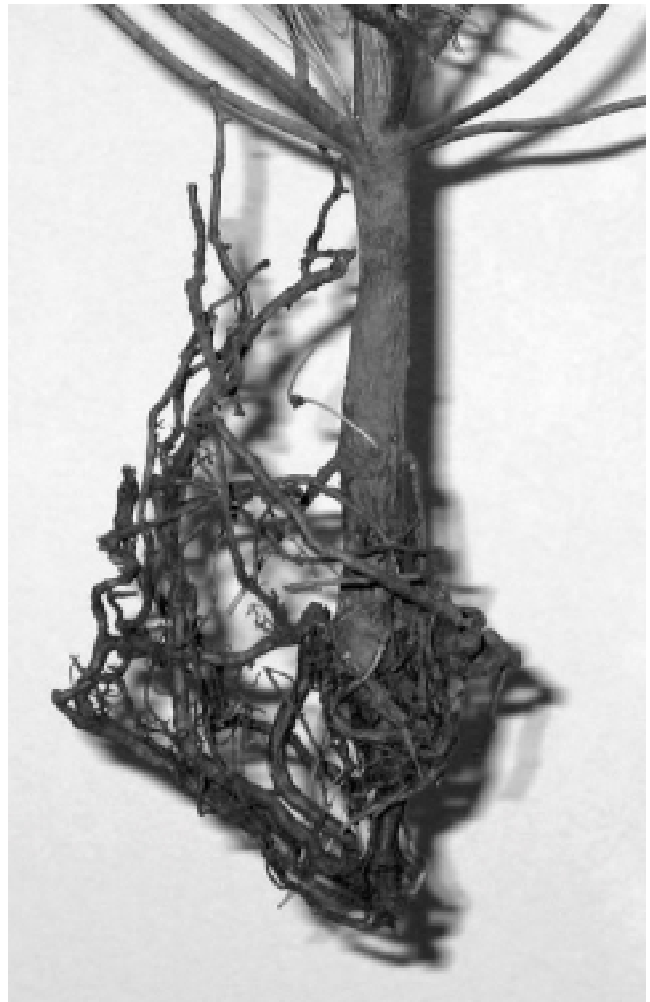

Fig. 1 Severe root malformation in a ***Pinus nigra*** seeding grown in a plug tray. Elongating roots were directed toward the container's drainage hole by interior vertical ribs. Roots reaching the bottom of the container were pruned by dessication and formed a solid mass, representing a physical barrier to further downward root elongation. Root tips reaching the container's drain hole after the physical barrier of desiccated root tips formed were redirected upwards. This seedling represents an example of 'U-type' root malformation.

(PAR) was recorded hourly and used to calculate the monthly average PAR level between sun rise and set. Temperatures were set at 24/18C (75/64F) day/night cycles seasonally adjusted for natural photoperiods. Trays were watered as needed to avoid water stress. The irrigation water pH was 7 with 35 mg/liter $CaCO_3$. After seedlings emerged, they were fertilized once per week with 100 mg/liter N of 20N–8.3P–4.6K (20–10–10) Peters water-soluble fertilizer (O.M. Scotts, Marysville, OH). The trays were set in the greenhouse in a randomized complete block design with two, single tray replicates.

In late July 2002, the number of seedlings per tray were counted, the survival percentage calculated, and the following data collected: number of seedlings with elongating lateral buds, seedling height and caliper. Ten seedlings from each tray were randomly selected and the substrate washed from the root system. Individual seedlings were severed at the root collar, oven-dried for 96 hr at 82C (180F) and dry

Table 1. Bulk density of a Canadian peat moss, vermiculite and perlite (1:1:1 by vol) substrate either compacted or not in 51-cell trays.

Treatment combination			Bulk density ($g\ cm^{-3}$)
Spinout[z]	Compaction[y]	Slits[x]	
No	No	No	0.57 ± 0.01[w]
Yes	No	No	0.55 ± 0.01
Yes	Yes	No	1.01 ± 0.08
No	Yes	No	1.10 ± 0.02
No	No	Yes	0.39 ± 0.00
No	Yes	Yes	0.71 ± 0.04

[z]For the treated cells, two coats of Spinout™ (a copper hydroxide latex paint mixture, Griffin Chemical Corp., Valdosta, GA) were applied to the interior surfaces of each cell. Cell trays were 51-cell trays (Grower Systems, Milwaukee, WI).
[y]Approximately twice the volume of substrate was compacted into individual cells for the compacted treatment, relative to the uncompacted treatment.
[x]Three 1.5 cm long, equally spaced, vertical slits were cut into each cell or cells were left intact.
[w]Each value is the mean of two, single tray replications; each tray had 51 cells. Each mean is followed by the standard deviation.

weights recorded. The shoot/root ratio was calculated from the dry weights. From the surviving seedlings, the number of seedlings with elongating buds was counted and converted to percent seedlings with elongating buds. The number of seedlings with root deformation were counted and the percent root malformation calculated from the seedlings harvested for the dry weight measurements. A root was classified as malformed when it circled more than 180° or was deflected upward (13).

In early August, forty-four seedlings from each treatment combination were transplanted without root pruning into No. 10 containers (Nursery Supplies, Fairless Hills, PA) to simulate lining out to a transplant bed. The substrate was pine bark:Comtil (3:1 by vol). Comtil is a composted municipal sewage sludge product, City of Columbus, OH. An additional forty-four seedlings were similarly transplanted but were first root pruned by removing the lower 2.5 cm (1 in) of the root ball. Therefore, there were four No. 10 sized containers, each with 22 seedlings resulting in two replications for each plug production and transplanting method combination. The No. 10 containers were placed in a randomized complete block design.

Transplanted seedlings were harvested during December 2002 by carefully removing the substrate from the root systems. Plant heights were recorded and seedlings were severed at the root collar. Roots were separated into three types: roots regenerated from the base of the original root ball; roots regenerated from the sides of the root ball; and, roots contained within the original cell volume. All plant parts were oven-dried for 96 hr at 82C (180F). Shoots dry weights were recorded and total root dry weight calculated by summing the three root dry weights for each individual seedling. Shoot:total root ratios were also calculated. The reduction in growth due to root pruning was obtained by subtracting the corresponding treatment means of the root-pruned seedlings from that of the seedlings with unpruned roots. Data were analyzed using ANOVA, contrast and regression procedures in SPSS for the personal computer (SPSS Institute, Chicago, IL).

Results and Discussion

Substrate densities ranged from 0.39 to 1.10 $g\ cm^{-3}$ in the cells with uncompacted substrate and slits, and cells with compacted substrate without slits, respectively (Table 1). Average monthly PAR level was 331, 470.1, 607.9, 728.6 and 1122.1 $\mu mol/m^2/s$ for March, April, May, June and July, respectively. Average day/night temperatures for March, April, May, June and July were respectively: 23/22C /(73/71F), 24/21C (76/70F), 24/22C (75/72F), 26/23C (78/73F), and 26/23C (79/74F), respectively. Average hourly relative humidity for these same months was 43/37, 56/52, 54/48, 72/68, and 74/62%, respectively.

All seedlings produced two flushes of growth. The first flush was about 2.5 cm (1 in) in length. Terminal and lateral

Table 2. Dry weight measurements of *Pinus nigra* seedlings five months after sowing, as affected by container coating, substrate compaction and air-root pruning slits.

Treatment combination			Dry weights[w]			
Spinout[z]	Compaction[y]	Slits[x]	Root (g)	Shoot (g)	Total plant (g)	Shoot/Root
No	No	No	0.47	0.65	1.12	1.41
Yes	No	No	0.59	0.82	1.41	1.47
Yes	Yes	No	0.60	1.21	1.81	2.05
No	Yes	No	0.74	1.05	1.79	1.48
No	No	Yes	0.56	0.71	1.27	1.33
No	Yes	Yes	0.67	1.14	1.81	1.84
Contrasts			P values			
Spinoutvs.noSpinout			0.71	0.05	0.19	0.06
Compactionvs.nocompaction			0.01	0.01	0.01	0.01
Slitsvs.noslits			0.77	0.91	0.94	0.91

[z]For the treated cells, two coats of Spinout™ (a copper hydroxide latex paint mixture, Griffin Chemical Corp., Valdosta, GA) were applied to the interior surfaces of each cell. Cell trays were 51-cell trays (Grower Systems, Milwaukee, WI).

[y]Approximately twice the volume of substrate was compacted into individual cells for the compacted treatment, relative to the uncompacted treatment.

[x]Three 1.5 cm long equally spaced, vertical slits were cut into each cell, or cells were left intact.

[w]Each value is a mean of two, single tray replications.

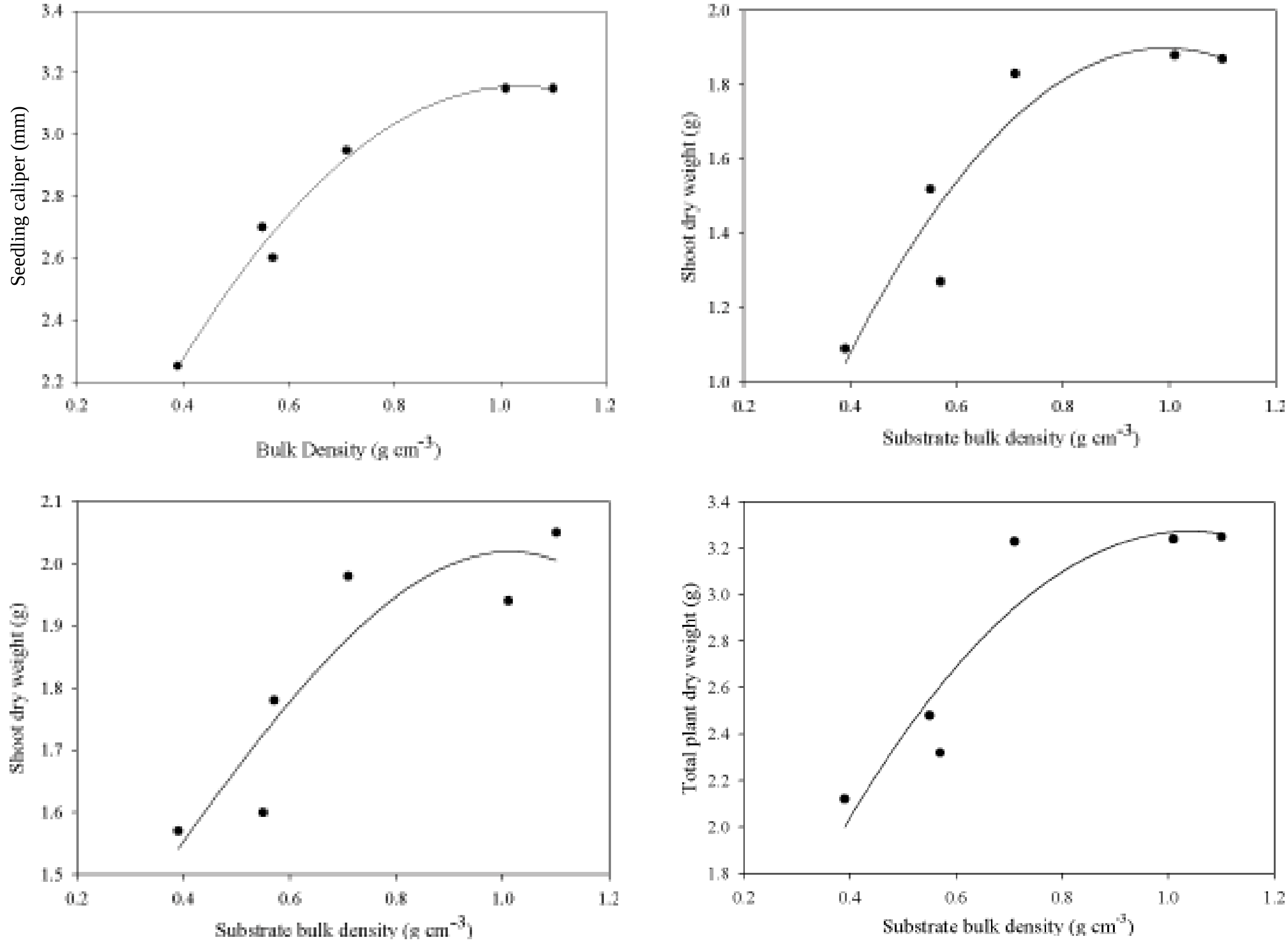

Fig. 2. ***Pinus nigra*** **seedling caliper five months after sowing seeds (top left), shoot dry weight of non-root pruned seedlings four months after transplanting (bottom left), shoot dry weight of root pruned seedlings four months after transplanting (top right) and total plant dry weight of root pruned seedlings four months after transplanting (bottom right) plotted against substrate bulk density. Seedling caliper five months after sowing seeds is predicted by the equation: $Sc = 0.81 + 4.52\ bd - 2.18\ bd^2$, $R^2 = 0.98$, $P = 0.002$, where Sc = seedling caliper (in mm), and bd = substrate bulk density (in g cm^{-3}); shoot dry weight of non-root pruned seedlings four months after transplanting is predicted by the equation: $Sdw_{n-rp} = 0.84 + 2.17\ bd - 1.01\ bd^2$, $R^2 = 0.82$, $P = 0.074$, where Sdw_{n-rp} = shoot dry weight (in g) and bd = substrate bulk density (in g cm^{-3}); shoot dry weight of root pruned seedlings four months after transplanting is predicted by the equation: $Sdw_{rp} = -0.40 + 4.64\ bd - 2.34\ bd^2$, $R^2 = 0.88$, $P = 0.040$, where Sdw_{rp} = shoot dry weight (in g) and bd = substrate bulk density (in g cm^{-3}); and total plant dry weight of root pruned plants is predicted by the equation: $TPdw = 0.018 + 6.26\ bd - 3.01\ bd^2$, $R^2 = 0.87$, $P = 0.049$, where TPdw = total plant dry weight (in g) and bd = substrate bulk density (in g cm^{-3}).**

buds began to form six to eight weeks after sowing, but a second flush, including both terminal and lateral buds, occurred within eight to 10 weeks after sowing. The second flush resulted in seedlings with low branches. There were no significant differences in height, survival, percent of seedlings with elongating lateral buds and root malformation among the different treatment combinations (data not shown). Average survival, seedlings with lateral buds and root malformation ranged from 87 to 97, 9 to 47, and 12 to 47%, respectively.

After five months of growth in the cells, seedlings grown in Spinout™-treated containers had significantly higher shoot dry weight than those in untreated containers (1.01 g vs. 0.89 g, Contrast 1, Table 2). Root, shoot, and total plant dry weights, and the shoot-to-root ratio were significantly greater when seedlings were grown in compacted substrate than uncompacted substrate (0.67 vs. 0.59 g, 1.13 vs. 0.73 g, 1.80 vs. 1.27 g, and 2.5 vs. 1.4 for root, shoot, total plant dry weights and shoot-to-root ratio, respectively [Contrast 2, Table 2]). Seedling caliper increased as substrate bulk density increased to 1.0 g cm^{-3} (Fig.2). The slit treatment did not affect any of the measured variables (Contrast 3, Table 2). The percentage of seedlings with malformed roots increased at substrate compaction levels of 0.71 and 1.01 g cm^{-3} (Treatments 2 and 6 respectively, Table 2). At the highest substrate compaction levels root circling was seen indicating that the internal vertical ribs were ineffective in directing root growth.

If seedlings were not root pruned before transplanting, root malformations formed during container production were evident four months later (data not shown). Transplanted seedlings grown in Spinout™-treated containers and not root pruned had significantly greater regenerated root dry weight from the sides of the root ball (0.35 g vs. 0.22 g) and a significantly higher interior root dry weight (1.80 g vs. 1.58 g) than seedlings grown in untreated containers four months after transplanting (Contrast 1, Table 3). Seedlings grown in

Table 3. **Dry weight distribution of *Pinus nigra* seedlings four months after simulated transplanting, as affected by container coating, substrate compaction and air-root pruning slits. The seedlings were not root pruned before transplanting.**

Treatment combination			Dry weights (g)[w]						
			Root growth						
Spinout[z]	Compaction[y]	Slits[x]	basal	side	interior	Total root	Total shoot	Total plant	Shoot/root ratio
No	No	No	0.68	0.17	0.68	1.53	1.78	3.31	1.24
Yes	No	No	1.06	0.34	0.61	2.01	1.60	3.61	1.19
Yes	Yes	No	0.45	0.36	0.80	1.60	1.94	3.54	1.24
No	Yes	No	0.40	0.26	0.97	1.63	2.05	3.68	1.31
No	No	Yes	0.50	0.24	0.61	1.35	1.57	2.92	1.20
No	Yes	Yes	0.54	0.23	0.87	1.80	1.98	3.78	1.17
Contrasts			P values						
Spinout vs. no Spinout			0.32	0.01	0.01	0.33	0.19	0.56	0.76
Compaction vs. no compaction			0.18	0.21	0.01	0.83	0.01	0.11	0.39
Slits vs. no slits			0.58	0.13	0.35	0.61	0.30	0.47	0.13

[z]For the treated cells, two coats of Spinout™ (a copper hydroxide latex paint mixture, Griffin Chemical Corp., Valdosta, GA) were applied to the interior surfaces of each cell. Cell trays were 51-cell trays (Grower Systems, Milwaukee, WI).

[y]Approximately twice the substrate volume was used to fill individual cells for the compacted as for the uncompacted treatment, resulting in compacted average bulk density of 0.94 and 0.50 g cm^{-3}, respectively.

[x]Three 1.5 cm long equally spaced, vertical slits were cut into each cell.

[w]Each value is a mean of two, 22 seedling replications.

compacted substrates had greater interior root dry weight (0.86 g vs. 0.63 g) than those grown in uncompacted substrates (Contrast 2, Table 3). Shoot dry weight was highest between 0.71 and 1.01 g cm^{-3} substrate bulk densities (Fig. 2). Vertical slits in the container walls had no effect on seedling growth (Contrast 3, Table 3).

When seedlings were root pruned before transplanting, those grown in Spinout™-treated containers had significantly greater shoot dry weight (1.7 g vs. 1.5 g) and higher shoot:root ratio (1 to 1.6 vs. 1 to 1.3) than those grown in untreated containers (Contrast 1, Table 4). Seedlings grown in compacted substrate had significantly higher regenerated root dry weight from the sides of the root ball than those grown in uncompacted substrates (0.18 g vs. 0.14 g, Contrast 2, Table 4). Dry weight of roots in the original root volume was higher in seedlings grown in uncompacted medium than compacted medium (0.53 vs 0.38 g), respectively, but the greatest root dry weight occurred in the no-Spinout™, compacted medium and no slits treatment combination (Table 4). Total root dry weight was higher in compacted substrate than in uncompacted substrate (1.4 g vs. 1.0 g, respectively, Contrast 2, Table 4). Shoot dry weight and total plant dry weight

Table 4. **Dry weight distribution of *Pinus nigra* seedlings four months after simulated transplanting, as affected by container coating, substrate compaction and air-root pruning slits. The seedlings were root pruned before transplanting.**

Treatment combination			Dry weights (g)[w]						
			Root growth						
Spinout[z]	Compaction[y]	Slits[x]	basal	side	interior	Total root	Total shoot	Total plant	Shoot/root ratio
No	No	No	0.37	0.11	0.57	1.05	1.27	2.32	1.28
Yes	No	No	0.30	0.17	0.50	0.96	1.52	2.48	1.72
Yes	Yes	No	0.42	0.17	0.15	1.37	1.88	3.24	1.44
No	Yes	No	0.36	0.20	0.82	1.38	1.87	3.25	1.42
No	No	Yes	0.35	0.15	0.52	1.03	1.09	2.12	1.06
No	Yes	Yes	0.41	0.17	0.17	1.40	1.83	3.23	1.33
Contrasts			P values						
Spinout vs. no Spinout			0.74	0.55	0.14	0.43	0.03	0.34	0.01
Compaction vs. no compaction			0.08	0.03	0.01	0.01	0.01	0.01	0.57
Slits vs. no slits			0.57	0.92	0.91	0.68	0.04	0.27	0.01

[z]For the treated cells, two coats of Spinout™ (a copper hydroxide latex paint mixture, Griffin Chemical Corp., Valdosta, GA) were applied to the interior surfaces of each cell. Cell trays were 51-cell trays (Grower Systems, Milwaukee, WI).

[y]Approximately twice the substrate volume was used to fill individual cells for the compacted as for the uncompacted treatment, resulting in compacted average bulk density of 0.94 and 0.50 g cm^{-3}, respectively.

[x]Three 1.5 cm long equally spaced, vertical slits were cut into each cell.

[w]Each value is a mean of two, 22 seedling replications.

Table 5. **Relative dry weight reduction four months after transplanting resulting from root pruning *Pinus nigra* seedlings at transplanting. Percent relative dry weight was calculated by subtracting the corresponding means in Tables 5 from those in Table 3 according to the formula: R_{DW} (%) = ($V_{Table\,3}$ – V_{Table5})/ ($V_{Table\,3}$ × 100), where R_{DW} (%) = percent relative dry weight, V_{Table4} = Table 3 mean and V_{Table5} the corresponding mean in Table 4.**

Tatment combination			Relative dry weights (%)					
			Root growth			Total root	Total shoot	Total plant
Spinout[z]	Compaction[y]	Slits[x]	basal	side	interior			
No	No	No	46	35	16	31	29	30
Yes	No	No	72	50	18	52	5	31
Yes	Yes	No	7	53	81	14	3	8
No	Yes	No	10	23	15	15	9	12
No	No	Yes	30	38	15	24	31	27
No	Yes	Yes	24	26	80	22	8	15

[z]For the treated cells, two coats of Spinout™ (a copper hydroxide latex paint mixture, Griffin Chemical Corp., Valdosta, GA) were applied to the interior surfaces of each cell. Cell trays were 51-cell trays (Grower Systems, Milwaukee, WI).

[y]Approximately twice the substrate volume was used to fill individual cells for the compacted as for the uncompacted treatment, resulting in compacted average bulk density of 0.94 and 0.50 g cm^{-3}, respectively.

[x]Three 1.5 cm long equally spaced, vertical slits were cut into each cell.

was higher in compacted substrate than in uncompacted substrate (Fig. 2). Seedlings grown in containers with slits had lower shoot-to-root ratio than those grown in containers without slits (1.2 vs. 1.5, Contrast 3, Table 4).

Regardless of the treatment combinations, there were no statistical differences in seedling mortality or seedling quality after five months of plug production, or seedling morphology after transplanting whether seedlings were root pruned or not. Although there were 2.4 times more seedlings with elongating lateral buds produced in cells without Spinout™, compacted substrate and slits, compared to those produced in cells without Spinout™, uncompacted substrate and slits (47 vs. 19%, Table 2), the difference was not significant. Thus, substrate compaction did not have an effect on the percent elongating lateral buds. The percentage of seedlings with malformed roots was twice as high in two treatments, (cells with Spinout™, compacted substrate, without slits, and cells without Spinout™, compacted substrate and slits) than in the other four treatment combinations; 30 and 47% vs. 12 to 16%, respectively.

The largest seedlings, highest shoot, root, and total plant dry weights were produced at substrate densities of 0.71 to 1.10 g cm^{-3} (Table 2). Caliper increased up to 1.01 g cm^{-3}, which suggests that seedlings should be produced at substrate bulk densities between 0.71 and 1.01 g cm^{-3}, if root malformation is not used as a quality indicator.

When the seedlings were transplanted without root pruning, root malformations were retained. Malformed roots inhibit translocation patterns (5, 6), increase plant shock, plant mortality (10), and mechanical instability (2, 3, 4, 5). Thus, before transplanting, malformed roots should be corrected to ensure long-term viability of the planting stock. Pruning the lowest 2.5 cm (1 in) of the root ball removed all root malformations caused by the physical blockage of the container drain holes and partially corrected circling root malformation found in cells with the highest substrate compaction levels.

When seedlings were root pruned, the relative loss in regenerated root dry weight from the base of the root ball was as high as 72% (cells with Spinout™, no substrate compaction, and no slits, Table 5). Relative regeneration root dry weight from the sides of the root ball was highest (50 and 53%) when seedlings were grown in cells treated with Spinout™, with or without substrate compaction and no slits. Relative interior root dry weight was reduced most (80 and 81%) when seedlings were grown in cells treated with Spinout™, substrate compaction, no slits or in no Spinout™, substrate compaction and slits. Total relative root dry weight was reduced most (52%) when seedlings were grown in cells treated with Spinout™, uncompacted substrate and no slits. Relative shoot and total plant dry weights were most reduced (29 and 31%, and 30 and 27%) when seedlings were grown in cells with no Spinout™, uncompacted substrate, no slits or in no Spinout™, uncompacted substrate and slits. Similar relative total plant dry weight reduction (31%) also occurred when seedlings were grown in cells with Spinout™, substrate uncompaction and no slits.

In summary, the largest seedlings were produced in three treatment combinations: cells treated with Spinout™, compacted substrate, without slits; no Spinout™, compacted substrate, without slits; or no Spinout™, compacted substrate with slits. The common treatment is substrate compaction. However, two of these treatment combinations decreased seedling quality (highest shoot-to-root ratio and highest percentage of root malformation): cells treated with Spinout™, substrate compaction without slits, and no Spinout™, substrate compaction with slits. If seedlings were not root pruned before transplanting, they tended to have similar total plant dry weight, except for seedlings grown in cells not treated with Spinout™, uncompacted substrate and slits. If seedlings were root pruned before transplanting, the treatments that resulted in the largest seedlings after five months in plug production also resulted in the largest seedlings four months after transplanting. The highest quality seedlings, those with the greatest dry weight and least root malformation were produced in cells without Spinout™, compacted substrate without slits. In contrast, Lodgepole and ponderosa pine seedlings grown in copper treated containers had greater regrowth potential than seedlings grown in untreated containers (7). Total plant dry weight four months after transplanting was not affected by growing the seedlings in Spinout™-treated containers. Based on our results, the highest quality transplanted *P. nigra* seedlings were produced in compacted substrate. Those seedlings were largest at the end of plug production and after transplanting, whether root pruned or not. Root pruning the lower 2.5 cm (1 in) of the root removed most root malformations. When *Pinus nigra* seeds are sown in March and grown under Ohio's natural photoperiod, a resting bud forms within six to eight weeks. However, those buds are capable of flushing; the result is higher quality (less leggy) seedlings.

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