RE-EVALUATING THE SIGNIFICANCE OF THE FIRST-ORDER LATERAL ROOT GRADING CRITERION FOR HARDWOOD SEEDLINGS

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ABSTRACT.—Numerous authors have reported on the importance of the number of first-order lateral roots (FOLR) when evaluating the morphological quality of nursery hardwood seedlings. Studies have shown that seedlings with a greater quantity of FOLR outperform seedlings with a lesser quantity of FOLR in the field. However, the FOLR measure may be limited in its ability to quantify root system morphology. Additionally, the number of FOLR is correlated with other morphological characteristics, and few studies have directly evaluated the importance of FOLR relative to other variables for predicting outplanting success. A trial in southern Indiana compared the ability of the initial number of FOLR to predict field performance for three hardwood species (black cherry, white oak, and northern red oak) relative to four other initial morphological variables (shoot height, stem diameter, root volume, and whole plant fresh weight). Regression analyses indicated that regardless of species, FOLR tended to be among the least effective predictors of total height and diameter after one field season. These results indicate that FOLR may provide a less accurate indicator of hardwood seedling morphological quality than other easily-measured variables.

The success of reforestation and afforestation operations may be improved if nurseries produce seedlings with target morphological and physiological characteristics that have been quantitatively linked with outplanting success (Rose et al. 1990). Morphological characteristics may be easily assessed by both nursery workers and field foresters. As such, these characteristics are often used to help evaluate seedling quality. Commonly-measured morphological characteristics include shoot height, stem diameter, and root system size (Rose et al. 1990).

Because shoot growth following planting is most limited by water availability (Burdett et al. 1984), roots must rapidly extend through the soil profile to re-establish root-soil contact and absorb water to minimize transplant shock (Sands 1984). The capacity of roots to do this is likely related to both seedling physiological quality (Ritchie and Dunlap 1980) and root system morphology. Various measurements of nursery seedling root system morphology have been proposed, including root mass, root volume, number of first-order lateral roots (FOLR), root length, and root area index.

Many measurements of root system morphology are either destructive, tedious and time consuming, or both. This generally limits their application to only selective research projects. Two root system measurements that are relatively rapid and non-destructive, and thus may have application in operation, are root volume and number of FOLR. Root volume is measured using the water displacement method (Burdett 1979). Nursery seedling root volume has been directly correlated with reforestation success for Douglas-fir (*Pseudotsuga menzeiseii* (Mirb.) Franco) and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) in the western United States (Rose et al. 1991a; Rose et al. 1991b; Rose et al. 1997). Carlson (1986) reported that root volume helps determine the potential for water uptake prior to new root growth in loblolly pine (*Pinus taeda* L.). Little research, however, has examined the importance of initial root volume in eastern deciduous tree species. Instead, the majority of research involving root morphology of these species has focused on FOLR (i.e., the number of first-order lateral roots exceeding 1 mm in diameter at junction with the tap root). Numerous studies have reported that hardwood seedlings with more FOLR perform better in the field than those with less FOLR (e.g.,

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Table 1.—Division of seedlings from each of the three species into four categories based on root volume (in cm^3, with means in parentheses).

	Root volume (cm^3)			
Species	R1	R2	R3	R4
Black cherry	4-17 (11.6)	18-31 (24.7)	32-56 (41.7)	57-265 (93.6)
Northern red oak	5-19 (15.0)	20-28 (23.9)	29-40 (34.0)	41-144 (59.3)
White oak	6-21 (16.2)	22-31 (26.4)	32-44 (38.3)	42-255 (61.2)

(Kormanik 1986; Teclaw and Isebrands 1993; Thompson and Schultz 1995; Schultz and Thompson 1996; Dey and Parker 1997; Clark et al. 2000; Ponder 2000)).

Though clearly linked to improved plantation establishment, measurement of number of FOLR likely does not provide the most accurate characterization of true root system size. Using the FOLR approach, no distinction is typically made between small and large FOLR. Additionally, lateral root length and the quantity of higher-order lateral roots (i.e., root fibrosity) are not accounted for. As such, root volume may provide a better assessment of seedling root system quality and subsequent outplanting performance for some hardwood species than the commonly used FOLR grading criterion. Additionally, although the significance of FOLR as an indicator of outplanting success for hardwood seedlings has been established, few studies have directly compared the effectiveness of FOLR for predicting seedling field performance to other easily-measured morphological variables. Thus, the objective of this report is to present preliminary first-year data from a study comparing the ability of five morphological variables (height, stem diameter, fresh weight, number of FOLR, and root volume) to predict outplanting success of three hardwood species in the Central Region.

Materials And Methods

In February 2002, nursery-grown (1+0) seedlings of three hardwood species commonly planted in the Central Region, northern red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), and black cherry (*Prunus serotina* Ehrh.), were obtained from the Indiana DNR State Nursery in Vallonia, IN. Approximately 1,000 seedlings from each species were washed free of soil, tagged, and measured in a lab at Purdue University for height, stem diameter, fresh weight, number of FOLR, and root volume. Seedlings in each species were then grouped into four root volume categories, representative of 25 percentiles within the root volume distribution for the population of seedlings from each species (table 1). Seedlings were stored in bags in a cooler at 2°C while not being sampled and prior to planting.

Seedlings from the resulting 12 treatments (three species × four root volume categories) were then outplanted into a replicated experimental design on a field planting site in southern Indiana at Purdue University's Southeast Purdue Agricultural Center (SEPAC) (39°01'N, 85°35'W) in April 2002. Twenty seedlings from each treatment were planted into each of ten blocks for a total of 2400 seedlings in the experiment. An electronic deer fence was installed immediately following planting and maintained throughout the experiment. Weed control using herbicide application was conducted prior to planting and as needed during the first growing season. Initial field height and stem diameter measurements were assessed on each seedling immediately following planting and were measured again in November 2002, following the first growing season.

Data were first analyzed using Analysis of Variance (ANOVA) to determine if seedling field performance differed among root volume categories. If the effect of root volume was significant ($p < 0.05$) in the ANOVA, Fisher's Least Significant Differences Procedure was used to identify significant differences ($a = 0.05$) among root volume treatments. Regression analyses were used to determine the relative importance of the five morphological variables for predicting plantation establishment success, and coefficient of determination values (R^2), were assessed for each regression. All data was analyzed using SAS Software (SAS Institute Inc, Cary, NC).

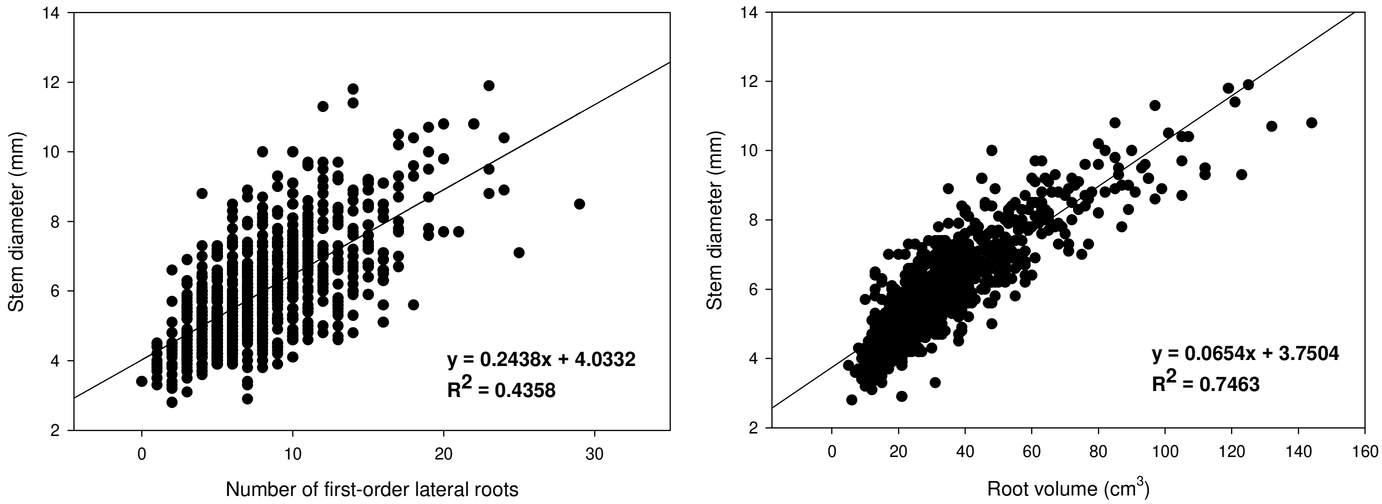

Figure 1.—Regression relationships using FOLR to predict stem diameter (top) and root volume to predict stem diameter (bottom) for northern red oak seedlings. Similar trends for this comparison existed for black cherry (R^2 = 0.80 vs. 0.53) and white oak (R^2 = 0.68 vs. 0.45).

Results

Analysis of the initial lab morphological data showed that regardless of species, root volume was a better predictor (i.e., higher R^2 values) of all other morphological variables than number of FOLR (data not shown). Figure 1 shows the relationships between both root volume vs. stem diameter and FOLR vs. stem diameter for northern red oak. The same trends were similar for the other two species. We found that seedlings with the same number of FOLR were often very different morphologically (fig. 2).

For each species, seedlings in larger root volume categories had a significantly greater initial field height and diameter than those in smaller root volume categories (table 2). Field height and stem diameter following the first growing season were again significantly larger for those seedlings in larger root volume categories (table 2). First-year height and diameter growth did not differ by root volume category for black cherry (table 2). For white oak, however, height and diameter growth were significantly different among root volume categories, with means increasing with increasing root volume (table 2). For northern red oak, height growth did not differ among root volume categories, but diameter growth was significantly lower for seedlings in R3 and R4 vs. those in R1 and R2 (table 2). Survival was > 88% for all root volume × species combinations and did not differ among root volume treatments for any species (table 2).

Table 3 shows regression analyses for morphological variables measured in the lab and field performance during the first growing season. In general, R^2 values for lab measurements and total height or diameter were relatively high, while those for lab measurements and height or diameter growth and survival were relatively low. With the exception of height:diameter, FOLR generally had the lowest R^2 value of any lab measurement for predicting total height or total diameter following the first growing season. For black cherry and northern red oak, R^2 values for height or diameter growth and survival were always less than 0.12. Height:diameter was the only significant variable predicting height growth for these two species. No variables were significant for diameter growth of black cherry, and FOLR was the only significant variable for diameter growth of northern red oak. Height:diameter had the highest R^2 value for survival of black cherry, and height was the only significant variable for survival of northern red oak. For white oak, height and root volume had the highest R^2 values for height growth, and height:diameter had the highest R^2 value for diameter growth. Diameter and FOLR were the best predictors of survival for white oak.

Discussion

Seedlings with more FOLR will generally perform better in the field than those with less FOLR. However, it is difficult to conclude that this is truly a function of the number of FOLR, or the correlation of FOLR with other variables. Many studies (e.g., (Kormanik 1986; Schultz and Thompson 1996; Teclaw and Isebrands 1993)) that have examined the ability of FOLR to predict outplanting success have not directly compared the significance of this attribute to other morphological variables. Those that have often report that, as a single variable, FOLR is not as important as others for predicting outplanting performance. Dey and Parker (1997) examined the ability of initial height, stem diameter, and FOLR to predict outplanting performance of northern red oak seedlings underplanted in a central Ontario shelterwood. The number of initial FOLR was not as important as initial height or stem diameter for predicting either second-year height or diameter of these seedlings. Additionally, initial stem diameter was more closely correlated with most measurements of root system morphology for seedlings excavated after two years than was initial height or FOLR. Interestingly, the correlation between initial and second-year FOLR was very weak and non-significant. Kaczmarek and Pope (1993a, b) also reported that initial height and in particular stem diameter, were more strongly related to seedling development in the field than was FOLR.

Though the current results are preliminary, FOLR was generally the weakest initial morphological variable for predicting seedling height and diameter following one growing season regardless of species. This adds further support to the concern that FOLR in itself should not be the sole morphological grading criterion for hardwood seedling. Rather, a combination of morphological characteristics may be necessary to adequately characterize seedling morphological quality (Kaczmarek and Pope 1993a).

Although FOLR is correlated with root system size, root volume likely provides a more accurate measure. Root volume better captures the discrepancy between small vs. large diameter roots, short vs. long lateral roots, and few vs. many second- and third-order lateral roots. We also found that particularly for seedlings with 15 or more FOLR, measurement of root volume was

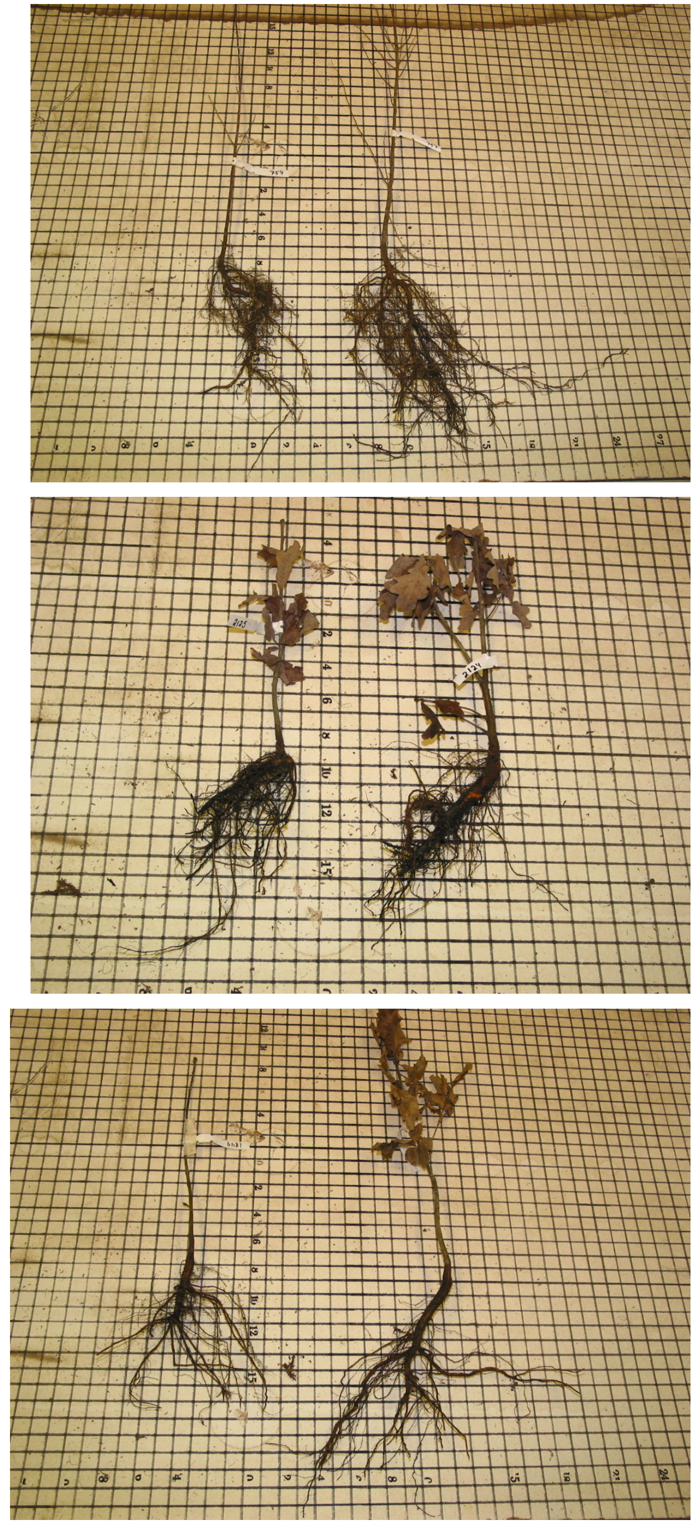

Figure 2.—Top photo: example black cherry seedlings, each with 12 FOLR and differences in height (91 vs. 76 cm), diameter (9.4 vs. 6.5 mm), fresh weight (98 vs. 50 g), and root volume (59 vs. 31 cm^3). Middle photo: example white oak seedlings, each with 16 FOLR and differences in height (27 vs. 30 cm), diameter (11.3 vs. 6.6 mm), fresh weight (93 vs. 47 g), and root volume (62 vs. 33 cm^3). Bottom photo: example northern red oak seedlings, each with 11 FOLR and differences in height (48 vs. 37 cm), diameter (7.4 vs. 5.5 mm), fresh weight (81 vs. 40 g), and root volume (53 vs. 28 cm^3).

Table 2.—Mean field parameters for different root volume categories in each species. For each field parameter and each species, means with the same letter within a row did not differ significantly at $\alpha = 0.05$.

	Initial height (cm)	Final height (cm)	Height growth (cm)	Initial diameter (mm)	Final diameter (mm)	Diameter growth (mm)	Survival (%)
				Black cherry			
R1	56.1 a	83.7 a	27.0 a	4.5 a	9.2 a	4.7 a	88 a
R2	72.5 b	100.8 b	28.4 a	5.7 b	11.1 b	5.3 a	93 a
R3	87.4 c	118.5 c	30.5 a	7.2 c	12.7 c	5.5 a	92 a
R4	107.1 d	131.7 d	24.4 a	9.9 d	14.7 d	4.7 a	95 a
				White oak			
R1	17.5 a	32.9 a	15.4 a	4.4 a	5.7 a	1.3 a	98 a
R2	21.2 b	39.8 b	18.6 b	5.3 b	7.0 b	1.7 ab	99 a
R3	25.8 c	48.0 c	22.4 c	6.4 c	8.1 c	1.6 ab	99 a
R4	35.3 d	57.7 d	22.4 c	7.8 d	9.9 d	2.1 b	99 a
				Northern red oak			
R1	29.3 a	41.0 a	11.8 a	4.0 a	5.4 a	1.4 b	98 a
R2	34.7 b	48.5 b	13.7 a	4.8 b	6.2 b	1.4 b	99 a
R3	41.9 c	55.7 c	13.8 a	5.7 c	6.9 c	1.1 a	99 a
R4	56.4 d	70.8 d	14.4 a	7.3 d	8.3 d	1.0 a	100 a

Table 3.—Regression coefficients of determination (R^2) values and corresponding significance levels between lab measurements and field measurements (total following one growing season, and growth) for three hardwood species. Bold text identifies the highest significant ($p < 0.05$) R^2 value for each field variable. For significant regressions, the symbol in parentheses indicates whether the slope of the linear regression line was positive or negative.

Lab measurement	Total height	Total diameter	Height growth	Diameter growth	Survival percentage
		Black cherry			
Height	0.71 *** (+)	0.37 *** (+)	0.05	0.02	0.04
Diameter	**0.75** *** (+)	0.50 *** (+)	0.01	0.001	0.08
FOLR	0.66 *** (+)	0.49 *** (+)	0.001	0.008	0.10 * (+)
Fresh weight	0.67 *** (+)	0.43 *** (+)	0.02	0.008	0.06
Root volume	0.67 *** (+)	0.44 *** (+)	0.02	0.006	0.07
Height:diameter	0.45 *** (-)	**0.52** *** (-)	**0.10** * (-)	0.09	**0.12** * (-)
		White oak			
Height	**0.87** *** (+)	**0.80** *** (+)	**0.36** *** (+)	0.17 ** (+)	0.09
Diameter	0.77 *** (+)	0.72 *** (+)	0.31 *** (+)	0.07	**0.12** * (+)
FOLR	0.59 *** (+)	0.52 *** (+)	0.23 ** (+)	0.02	**0.12** * (+)
Fresh weight	0.83 *** (+)	0.77 *** (+)	0.35 *** (+)	0.10 * (+)	0.10 * (+)
Root volume	0.84 *** (+)	0.77 *** (+)	**0.36** *** (+)	0.10 * (+)	0.10 * (+)
Height:diameter	0.48 *** (-)	0.43 *** (+)	0.21 ** (+)	**0.34** *** (+)	0.01
		Northern red oak			
Height	0.90 *** (+)	0.77 *** (+)	0.02	0.04	**0.11** * (+)
Diameter	**0.91** *** (+)	**0.82** *** (+)	0.08	0.03	0.08
FOLR	0.75 *** (+)	0.57 *** (+)	0.07	**0.10** * (-)	0.10
Fresh weight	0.91 *** (+)	0.77 *** (+)	0.06	0.05	0.09
Root volume	0.90 *** (+)	0.76 *** (+)	0.06	0.06	0.09
Height:diameter	0.20 ** (-)	0.13 ** (-)	**0.11** * (-)	0.03	0.06

*p < 0.05; ** p < 0.01; *** p < 0.0001

less time consuming than that of number of FOLR. As such, root volume may provide a more effective quantitative measurement of root system morphology than FOLR. In the present study, root volume had higher R^2 values than FOLR for predicting total height and diameter of both white oak and northern red oak following one growing season. Continued research under a variety of environmental conditions will help determine the importance of various morphological variables for predicting hardwood seedling outplanting success.

Acknowledgments

Ron Overton and Bob Karrfalt assisted with lab measurements. Anthony Davis, Amy Ross-Davis, and Barrett Wilson assisted with field measurements. Indiana DNR Vallonia Nursery donated seedlings for this experiment. Financial support for this research was provided by the Mary S. Rice Farm Fund.

Literature Cited

Burdett, A.N. 1979. **A nondestructive method for measuring the volume of intact plant parts**. Canadian Journal of Forest Research. 9:120-122.

Burdett, A.N.; Herring, L.J.; Thompson, C.F. 1984. **Early growth of planted spruce**. Canadian Journal of Forest Research. 14:644-651.

Carlson, W.C. 1986. **Root system considerations in the quality of loblolly pine seedlings.** Southern Journal of Applied Forestry. 10:87-92.

Clark, S.L.; Schlarbaum, S.E.; Kormanik, P.P. 2000. **Visual grading and quality of 1-0 northern red oak seedlings.** Southern Journal of Applied Forestry. 24:93-97.

Dey, D.C.; Parker, W.C. 1997. **Morphological indicators of stock quality and field performance of red oak (*Quercus rubra L.*) seedlings underplanted in a central Ontario shelterwood**. New Forests. 14:145-156.

Kaczmarek, D.J.; Pope, P.E. 1993a. **Covariate analysis of northern red oak seedling growth.** In: Brissette, J.C., ed. Proceedings, 7th Biennial Southern Silvicultural Research Conference; 1992 Novermber 17-19; Mobile, AL. Gen. Tech. Rep. SO-93. New Orleans, LA: US Department of Agriculture, Forest Service, Southern Forest Experiment Station: 351-356.

Kaczmarek, D.J.; Pope, P.E. 1993b. **Seedling morphology related to growth and survival of northern red oak**. In: Thompson, J.R.; Schultz, R.C.; Van Sambeek, J.W., eds. Fifth Wokshop on Seedling Physiology and Growth Problems in Oak Plantings. Gen. Tech. Rep. NC-158. US Department of Agriculture, Forest Service, North Central Forest Experiment Station: 11.

Kormanik, P.P. 1986. **Lateral root morphology as an expression of sweetgum seedling quality**. Forest Science. 32:595-604.

Ponder, F., Jr. 2000. **Survival and growth of planted hardwoods in harvested openings with first-order lateral root differences, root-dipping, and tree shelters**. Northern Journal of Applied Forestry. 17:45-50.

Ritchie, G.A.; Dunlap, J.R. 1980. **Root growth potential - its development and expression in forest tree seedlings**. New Zealand Journal of Forestry Science. 10:218-248.

Rose, R.; Carlson, W.C.; Morgan, P. 1990. **The target seedling concept**. In: Rose, R.; Cambell, S.J.; Landis, T.D., eds. Proceedings of the combined meeting of the Western Forest Nursery Associations; 1990 August 13-17; Roseburg, OR. Gen. Tech. Rep. RM-200. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 1-8.

Rose, R.; Atkinson, M.; Gleason, J.; Sabin, T. 1991a. **Root volume as a grading criterion to improve field performance of Douglas-fir seedlings**. New Forests. 5:195-209.

Rose, R.; Gleason, J.; Atkinson, M.; Sabin, T. 1991b. **Grading ponderosa pine seedlings for outplanting according to their root volume**. Western Journal of Applied Forestry. 6:11-15.

Rose, R.; Haase, D.L.; Kroiher, F.; Sabin, T. 1997. **Root volume and growth of ponderosa pine and Douglas-fir seedlings: a summary of eight growing seasons.** [Erratum: Oct 1997, v. 12 (4), p. 134.]. Western Journal of Applied Forestry. 12:69-73.

Sands, R. 1984. **Transplanting stress in radiata pine**. Australian Forest Resources. 14:67-72.

Schultz, R.C.; Thompson, J.R. 1996. **Effect of density control and undercutting on root morphology of 1+0 bareroot hardwood seedlings: five-year field performance of root-graded stock in the central USA**. New Forests. 13:297-310.

Teclaw, R.M.; Isebrands, J.G. 1993. **An artificial regeneration system for establishing northern red oak on dry-mesic sites in the Lake States, USA.** Annals of Forest Science. 50:543-552.

Thompson, J.R.; Schultz, R.C. 1995. **Root system morphology of *Quercus rubra L.* planting stock and 3-year field performance in Iowa**. New Forests. 9:225-236.