DEVELOPMENT AND FUNCTION OF THE ROOT SYSTEMS OF SOUTHERN PINE NURSERY STOCK

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Abstract.--Root system morphology and physiology of nursery stock are important determinants of outplanting success. Literature reviewed here on the effects of nursery practices on root development and function reflects increasing research interest. Those findings lead to recommendations about how to produce seedlings with high quality root systems.

Additional keywords: Nursery practice, root growth, root morphology.

In his classic monograph, Planting the Southern Pines, Wakeley (1954) wrote: "The ability of planted southern pines to overcome drought and attain high initial survival seems to depend...upon formation of considerable new root tissue promptly after planting." The importance of the planted root system to reforestation success cannot be overemphasized. For seedlings to survive and grow, they depend on water and nutrients that must be obtained from the soil through the root system. However, the root systems of seedlings are subject to many types of damage between the time they are lifted from the nursery and their outplanting in reforestation projects.

Lifting, handling, and planting seedlings stresses their root systems in several ways. Shoots suffer less damage than roots because seedlings are lifted during the winter when there is rarely any succulent tissue. Root systems, however, are subject to many of the fine roots being broken off during lifting; Wakeley (1954) estimated that 50% of a pine seedling's root system could be lost during lifting without visible evidence of damage. Nambiar (1980) concluded that the total length of roots transplanted does not exceed 25% of that in the nursery. Roots often suffer further injury from desiccation and mechanical damage during handling at the nursery, in storage, during transport to the planting site, and during the planting operation. Furthermore, the roots extant when seedlings are transplanted seldom have as good contact with the soil as do the roots of plants that germinate and grow in place. Transplanted seedlings, therefore, have reduced water- and nutrient-absorbing capacity compared to what they had prior to lifting, but they have the same surface area for transpiration. Because of the imbalance between absorption and transpiration surface areas brought about by lifting, handling, and planting, even seedlings planted under ideal conditions suffer some degree of transplanting stress (Rietveld 1989). Reduced absorptive capacity can lead to severe and often prolonged water deficits in transplanted trees. In the Front Range of the Rocky Mountains of Colorado (Baldwin and Barney 1976), and in Sweden (Orlander 1986), plant moisture stress (PMS) levels of transplanted pine seedlings took two years or longer to recover to the level of established control seedlings.

Genetics also play a critical role in determining root system development, both in the nursery and after outplanting. Although nursery managers normally

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have little control over the seed sources or families they grow, when applying any nursery culture practice one should take into account the importance of genetics to root development.

The impacts of reforestation practices on seedling root systems must be an important concern to nursery managers and silviculturists. The damage potential to root systems between lifting and planting and the genetic patterning of root development can both be addressed through prudent application of several key practices in the nursery and during storage and handling. Any treatment that a manager applies affects seedling root systems, and, as Wakeley stated, survival will largely depend on the quality of the root systems.

This paper reviews pertinent literature describing the effects of various nursery practices on the morphology and physiology of southern pine seedling root systems. The practices that will be emphasized are those that have the greatest impact on root development and function: seedbed density, fertilization, irrigation, root culture, and lift and store procedures.

NURSERY PRACTICE AND ROOT SYSTEM DEVELOPMENT

Seedbed Density

The size of seedling root systems, measured as ovendry weight or as volume of water displaced, increases as seedbed density decreases (Brissette and Carlson 1987a,b, Carlson 1986, Hatchell 1985, Mexal 1981, Nebgen and Meyer 1985, Rowan 1985, Switzer and Nelson 1963). The relationship between seedbed density and root system size tends to be very strong. In a study with shortleaf pine, seedbed density explained 98% of the variation measured in mean root volume for seedlings grown at a range of densities averaging between 11 and 34 seedlings per ft^2 (Figure 1) (Brissette and Carlson 1987a). Over a range of seedbed densities from 10 to 45 seedlings per ft^2, density accounted for 77% of the variation in root weight of loblolly pine, and 90% of the variation in the number of first-order lateral roots (Rowan 1985). The number of first-order lateral roots has been shown to be a good indicator of pine seedling quality (Hallgren and Tauer 1989, Kormanik 1989, Nambiar 1980), probably because lateral roots represent the sites for new root initiation and elongation (Carlson 1986, DeWald and Feret 1988).

Root growth potential (RGP) is a measure of the ability of nursery stock to initiate and elongate new roots. RGP is most often measured as the number of new roots longer than some specified length--e.g. > 1 cm--although it is sometimes measured as length or projected surface area. In general, RGP is directly related to field survival--that is, the greater the RGP, the better is field performance. When the seedlings encounter water stress during establishment, survival is most directly linked to RGP.

Like root weight or volume, RGP increases with decreasing seedbed density (Brissette and Carlson 1987b, South and others 1989). It is likely that RGP is related to root system size and number of first-order laterals, with more new roots produced on large, rather than small root systems (Figure 2) (Brissette and Roberts 1984, Carlson 1986). Therefore, the effect that seedbed density has on root system morphology may account for the apparent relationship between density and RGP (South and others 1989).

The expression of RGP is controlled by a complex interaction of a number of seedling and environmental factors. In general, however, treatments that increase root system size or the number of lateral roots should also increase RGP--if the other factors affecting RGP remain constant.

Before new root growth commences, a transplanted seedling must depend on the planted roots for water and nutrient uptake. Root system size affects the seedling's ability to take up water and nutrients. Among loblolly pine seedlings that had not yet developed any new roots, Carlson (1986) found a positive relationship between root volume and root system absorptive capacity. However, once new roots elongate, the area of new root tissue is more important than the total root system size because new roots are much more absorbent than old roots (Brissette 1990, Carlson 1986, Chung and Kramer 1975, Sands and others 1982).

Fertilization

The fertilization regimen followed at a nursery can affect root system morphology and perhaps physiology. Fertilization effects on root systems depend on the nutrient studied.

The level of soil phosphorus (P) apparently has little impact on the size of shortleaf, loblolly, Virginia, or slash pine root system size, as long as the soil is not deficient in P or other nutrients (Brissette and Carlson 1987b, Fowells and Krauss 1959, McGee 1963). The addition of P, however, increased the shoot-to-root ratio of slash pine, suggesting that shoot growth was stimulated even if root growth was not (McGee 1963).

Adding potassium (K) may increase root growth relative to shoot growth because the shoot-to-root ratio declined with increasing K levels for slash pine seedlings (McGee 1963).

Nitrogen (N) is of particular interest; it is traditionally supplied to nursery stock in topdressings throughout the early part of the growing season. Increasing the total amount of applied N increases the dry weight of both the shoots and the roots. Typically shoot dry weight is increased more than is root dry weight so that as total applied N increases so does the shoot-to-root ratio (Fowells and Krauss 1959, McGee 1963, Switzer and Nelson 1963). However, that general trend is not always the case. In research with shortleaf pine, increasing N from 49 to 152 lb/a produced a significant linear increase in root volume; the highest N rate produced shorter, larger-diameter seedlings than did the lower rates of N (Brissette and Carlson 1987b). Furthermore, these short, stocky seedlings had the most growth during the first year after outplanting2.

The timing of N application can have significant effects. Fertilizing with N at 30 lb/a in August significantly increased root dry weight, but not shoot dry weight, of slash pine seedlings compared with the controls, but shoot-to-root ratios did not differ (Duryea 1990). In longleaf pine, application of N at 150 lb/a in late October resulted in as much as a 27% increase in the dry

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[2] Barnett, J. P. Interim Report #4 to the Task Force on Shortleaf Pine Artificial Regeneration in the Ouachita and Ozark Mountains. (Unpublished Report dated March 23, 1990). USDA For. Serv. South. For. Exp. Stn., Pineville, LA.

weight of the roots and bud when the seedlings were lifted the following March (Hinesley and Maki 1980).

Fertilization can affect root morphology in other ways. Relatively low levels of N and P in sand culture enhanced the development of mycorrhizal roots in loblolly and Virginia pine seedlings, whereas mycorrhizae structures were not observed at higher levels of those nutrients (Fowells and Krauss 1959). In a container seedling study of longleaf and shortleaf pines, however, high levels of fertilization in a peat-vermiculite medium did not seem to inhibit the development of Thelephora terrestris mycorrhizae (Barnett 1982).

The effects of fertilization on RGP are not clearly defined, partly because any influence that fertilization has on RGP is confounded by the impact on root morphology. In a shortleaf pine nutrient-density study by Brissette and Carlson (1987b), RGP was affected by an interaction between seedbed density and total N applied. At a low mean density of 12.6 seedlings per ft^2, RGP increased with increasing N, but, at mean densities of 20 or more, the relationship between N and RGP was not consistent.

A recent innovation in topdressing with N is application of the fertilizer at an increasing rate as the seedlings grow, rather than the conventional method of several applications at equal rates. In container red pine, this technique produced larger seedlings with smaller shoot-to-root ratios compared to the conventional method (Timmer and Armstrong 1987). Application of N at 80 lb/a, either at equal or increasing rates, interacted with half-sib family to influence root system morphology and RGP of shortleaf pine seedlings (Figure 3) (Brissette and others 1989b). Among the three families studied, the responses varied. Family 138 showed few morphological effects resulting from the method of N application, but it did have greater RGP under the increasing rate regimen. The application method affected the root morphology of Families 322 and 342, but of those two, only Family 342 showed increased RGP from the increasing rate treatment.

The results of the study by Brissette and others (1989b) suggest that the increasing-rate method of N application may improve seedling root quality. However, in a similar study conducted with loblolly pine at a nursery with higher initial fertility the method of N application had no apparent effect on either root or shoot morphology[3]. It appears likely that the nursery soil properties and, perhaps, the fertilization history determine to what extent nutrient management can alter root system morphology or physiology.

Irrigation

Water stress most often limits plant growth. In general, a stress will cause a shift in resource partitioning within a plant, which increases allocation to those organs that depend most on the growth-limiting element of the environment (Hunt and Nicholls 1986). For example, limited water availability should increase root development at the expense of shoot growth because more root mass is needed to absorb sufficient water.

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[3]Brissette, J. C. The effects of nitrogen fertilization on seedling characteristics and field performance of bare-root loblolly pine. (Unpublished study results). USDA For. Serv. South. For. Exp. Stn., Pineville, LA.

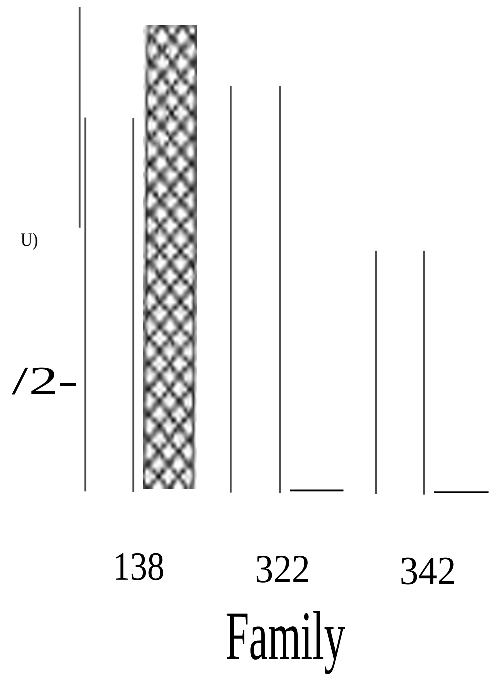

Figure 3. Effects of half-sib family and whether N was applied in equal increments (solid bars) or at a geometrically increasing rate (cross hatched bars) on the RCP (projected surface area) of bare-root shortleaf pine seedlings (from Brissette and others 1989b).

In a pot study of several seed sources of loblolly pine, dry weight partitioning between roots and shoots of seedlings was compared under either well watered or recurring drought conditions (Bongarten and Teskey 1987). Compared to the well watered seedlings, the water-stressed plants allocated significantly more of their growth to the roots than to the shoots. However, one year after germination, the total dry weight of the stressed seedlings averaged only 30% that of the well watered plants. Although it is feasible to increase root growth relative to shoot growth by limiting water in the nursery, care must be exercised not to allow seedlings to be stressed to the extent that root growth as well *as* shoot growth is markedly reduced.

In a study of nursery irrigation late in the growing season (September to November), irrigated seedlings had significantly heavier root systems than did non-irrigated seedlings (Williams and others 1988). Thus, timing irrigation to coincide with a period of root growth can also enhance root development.

In the study by Williams and others (1988), fall irrigation had no effect on RGP. In a study by Hennessey and Dougherty (1984), loblolly pine seedlings that had been moderately water-stressed by subjection to a predawn xylem pressure potential (or PMS) of 7.5 bars before irrigating had nearly three times as much RGP as control seedlings watered when predawn PMS reached only 2.5 bars.

Root Culture

Root culture in the nursery consists of undercutting, wrenching, and lateral root pruning. At some nurseries, roots are laterally pruned and undercut shortly before lifting to make seedling harvesting easier and less damaging to the root systems. At other nurseries, various combinations of undercutting, wrenching, and lateral root pruning are used as techniques to develop more fibrous root systems. The extent to which root culture alters root system morphology depends upon the timing of the treatment and, probably, on the nursery soil as well. Root culture techniques may also interact with other nursery practices such as seedbed density and irrigation and fertilization regimens. Consequently, the results of root-pruning studies in the nursery have not been consistent.

Shoulders (1965) reported that undercutting at 7 in. in early August retarded the height growth of loblolly and slash pine seedlings but was inconsistent in its effects on survival; he did not discuss effects of the treatment on root morphology. For longleaf pine, however, undercutting did improve survival (Shoulders 1965). For loblolly pine seedlings, Tanaka and others (1976) showed that undercutting followed by periodic wrenching reduced shoot height and diameter, increased the proportion of lateral roots, and improved survival. A later study at the same nursery (Venator and Mexal 1981) showed no effects of wrenching on root morphology or survival of loblolly pine. In a recent study at the Ashe nursery in southern Mississippi[4], bi-weekly wrenching starting in either July or August increased the estimated root surface area, or root area index (RAI), compared to unwrenched seedlings (Figure 4). For loblolly pine grown in Virginia, Dierauf and Olinger (1982) showed that undercutting reduced shoot growth in the nursery beds and slightly improved first-year field growth, but they did not measure treatment effects on root morphology. In a follow-up study, Feret and Kreh (1986) showed that undercutting in August and September reduced shoot height and diameter, and increased root dry weight compared to untreated seedlings; moreover, undercutting resulted in a slight increase in RGP, although the effect was not prominent ($p = 0.20$).

Lift and Store Procedures

Lift date and storage duration can affect both seedling morphology and physiology. Although height growth normally stops in the nursery before the lifting season begins, diameter and root growth often continue throughout the winter (Huberman 1940, Garner and Dierauf 1976, Zimmermann and Brown 1971). For loblolly pine seedlings growing in a Virginia nursery, shoot dry weight increased 45% between October 1 and March 1, while root dry weight increased 189% (Garner and Dierauf 1976). Thus, the shoot-to-root ratio decreased from 5.5 to 2.8 over that period.

The expected development of RGP for tree seedlings growing in temperate climates is an increase throughout the fall and winter, a peak in mid-winter, then a relatively rapid decline just prior to budbreak (Ritchie and Dunlap

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[4] Brissette, J. C. The effects of root pruning on dry matter partitioning and field performance of bare-root loblolly pine seedlings. (Unpublished study results). USDA For. Serv. South. For. Exp. Stn., Pineville, LA.

1980). Because of the warm climate, the southern pines do not adhere to that pattern as strictly as do northern or northwestern conifers. In fact, a number of seasonal patterns in RGP have been reported for pine seedlings grown at various locations in the South.

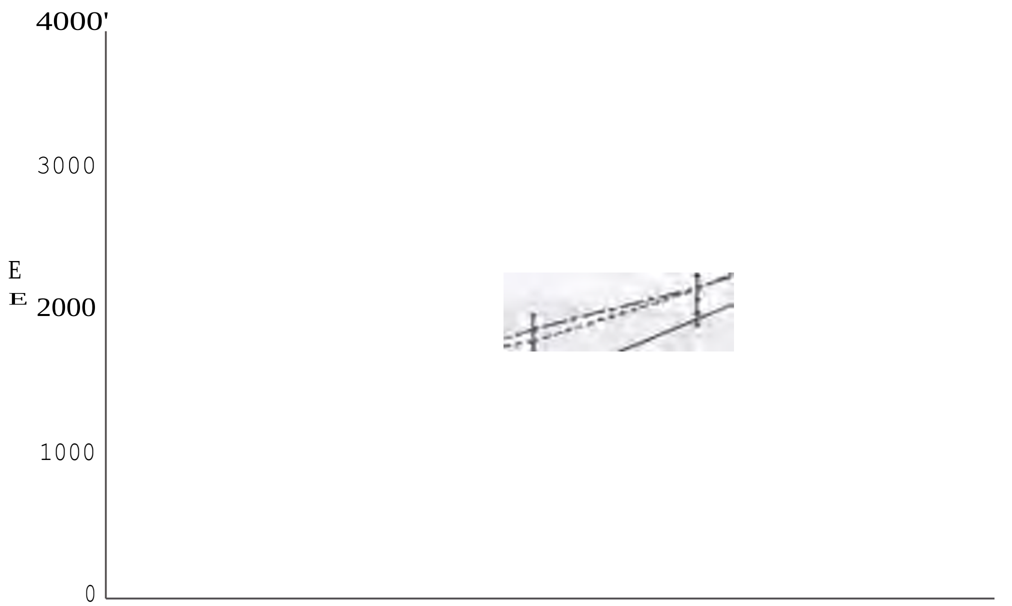

Figure 4. Effects of bi-weekly wrenching starting in either July or August on the growth in root area index (RAI) of loblolly pine seedlings sown in mid-April. Vertical bars represent + 1 standard error at each measurement date.

The use of accumulated chilling in the nursery beds (hours between 32 and 46 °F at 8 in. above the soil surface) to define when stock is lifted, rather than calendar date, eliminates the effects of year-to-year variation in weather conditions. When the RGP of several seed sources of loblolly, longleaf, and slash pines grown at the Ashe nursery was evaluated, Brissette and others (1989a) found a mid-winter peak in RGP at approximately 600 chilling hours for most sources, but some had a nearly constant RGP throughout the lifting season (Figure 5). For loblolly pine from nurseries in both South Carolina and Virginia, Barden and others (1987) reported a decline in RGP after a mid-winter peak, followed by a sharp increase late in the lifting season. The RGP of shortleaf pine grown in southeastern Oklahoma was greatest in December and declined steadily throughout the rest of the winter (Hallgren and Tauer 1989). These inconsistent patterns in RGP development are indicative of the complexity of the relationships among seedling morphology, seedling physiology, the nursery environment, and nursery culture practices.

The duration of cold storage can also affect RGP, depending upon when the seedlings are lifted. For loblolly pine seedlings grown at a nursery in southwestern Arkansas, Carlson (1985) found that storage for three weeks sharply reduced the RGP of stock lifted after 207 hours of chilling, but not after 734 chilling hours. Cold storage of seedlings lifted after about 600 chilling hours reduced the RGP of most of the seed sources of loblolly, longleaf, shortleaf, and slash pine seedlings grown at the Ashe nursery (Figure 5) (Brissette and others 1989a).

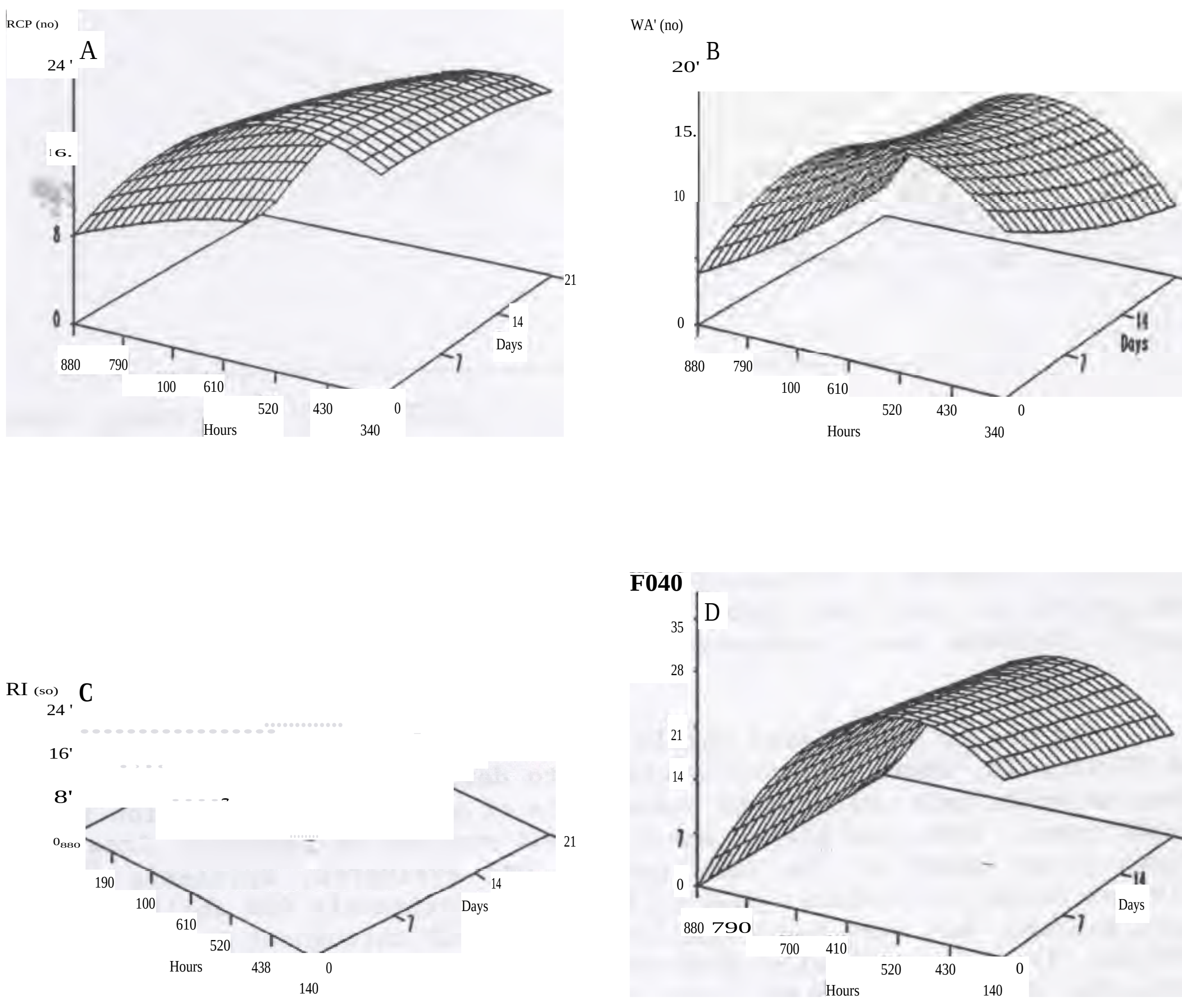

Figure 5. Effects of accumulated chilling hours (32-46 °F) and days in cold storage on the RGP (number of new roots > 1 cm long) of various seed sources growth at the W. W. Ashe nursery in southern Mississippi: A = mixture of several sources of loblolly pine; B = longleaf pine from northern Alabama; C – longleaf pine from Louisiana; D – mixture of Alabama and Florida slash pine (from Brissette and others 1989a).

Seedlings lifted much before or after their optimum lifting times are most likely to suffer a loss in root-system quality; those stored for any length of time before planting are especially likely to show negative effects (Garber and Mexal 1980). One of the reasons for a decline in seedling quality in storage is the presence of root pathogens. Mixing a fungicide with the clay slurry used to coat the roots before storage can control pathogens and markedly improve survival (Barnett and others 1988). The results have been especially dramatic for longleaf pine; without a fungicide its field survival declines rapidly with increasing storage duration.

These varied results suggest that optimum lifting and storing procedures--including the amount of accumulated chilling and its synergistic effects on the timing of lifting and duration of storing--vary by nursery, species, seed source, and sensitivity to root pathogens.

CONCLUSIONS AND RECOMMENDATIONS

It is evident from the work on nursery practices that few generalities about their effects on root system development apply to all southern pine nurseries. One generality that can be made is that reducing seedbed density improves root system morphology, whether it is measured as dry weight, volume, or number of lateral roots. The degree to which other nursery practices like fertilization, irrigation, and root culture influence roots depends on a number of other factors such as timing of application, chemical and physical properties of the soil, and nursery climate. Furthermore, all these factors can interact, making an interpretation of their effects on root system development and function much more difficult.

Although a specific prescription for improving root quality may not be possible, a number of recommendations can be drawn from this review:

1. Reduce seedbed density to the lowest economically feasible for your nursery. This is best assured by knowing the germination rate for each seedlot and the expected losses for each location in the nursery. On the basis of that knowledge, sow for the desired density. If an "insurance factor" is needed, it is better to sow some extra seedbed length than to increase seedling density.

2. Fertilize to maintain healthy, vigorous seedlings. Use soil tests to determine how much P, K, and other nutrients are needed for a seedling crop. Do not over-fertilize with N; it stimulates shoot growth more than root growth and it probably has little effect on RGP. Furthermore, high levels of N and P in the soil can inhibit mycorrhizae development. Comparing fertilization records with appropriate plant nutrient analyses can help determine how much N is correct for your nursery. Applying N at an increasing rate rather than in equal amounts might improve root morphology and RGP at your nursery.

3. After germination is complete, monitor irrigation needs. Irrigate when seedlings need water, not on a fixed schedule. When seedlings have neared the desired height, reduce irrigation to induce moderate--not severe--water stress. Water stress is best monitored by measuring the xylem pressure potential (PMS) of the

seedlings themselves. PMS can be easily measured with a pressure chamber. A moderate water stress can be induced by withholding irrigation until average predawn PMS is no more than about 7 bars. Severe water stress can develop if predawn PMS is greater than about 10 bars. After shoot growth stops and buds set, fall irrigation may stimulate root development.

4. Determine your objectives for root culture practices: to control height growth, to improve root morphology, to do both of these, or just to make lifting easier. Any of these objectives may be appropriate depending on the species and the nursery. Undercutting followed by repeated wrenching may stimulate root development while inhibiting shoot growth.

5. Determine the optimum dates for lifting the various seedlots grown at your nursery using survival records or RGP test results. If possible, use accumulated chilling hours rather than calendar date to schedule lifting. The closer seedlings are lifted to their optimum lifting period, the longer they will maintain their quality in storage. Incorporating a fungicide--for example benomyl at 5% active ingredient (ai)--into the packing medium improves storability, especially of longleaf pine. Regardless of when seedlings are lifted or whether a fungicide is used in packing, it is always best if they are planted as quickly as possible.

In recent years, root systems have received increasing research emphasis. The results of that research are not always consistent, but the work has expanded our awareness of the importance of roots and the complexity of the interactions that determine root morphological and physiological quality.

LITERATURE CITED

Baldwin, V. C.; Barney, C. W. 1976. Leaf water potential in planted ponderosa and lodgepole pines. Forest Science 22(3):344-350.

Barden, Charles J.; Feret, Peter P.; Kreh, Richard E. 1987. Root growth potential and outplanting performance of loblolly pine seedlings raised at 2 nurseries. In: Phillips, Douglas R., ed. Proceedings, fourth biennial southern silvicultural research conference; 1986 November 4-6; Atlanta, GA. Gen. Tech. Rep. SE-42. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 237-244.

Barnett, J. P. 1982. Relating field performance of containerized longleaf and shortleaf pine to mycorrhizal inoculation and initial size. In: Proceedings, 7th North American forest biology workshop; 1982 July 26-28; Lexington, KY. Lexington, KY: University of Kentucky: 358-367.

Barnett, James P.; Brissette, John C.; Kais, Albert G.; Jones, John P. 1988. Improving field performance of southern pine seedlings by treating with fungicides before storage. Southern Journal of Applied Forestry. 12(4):281-285.

Bongarten, Bruce C.; Teskey, Robert O. 1987. Dry weight partitioning and its relationship to productivity in loblolly pine seedlings from seven sources. Forest Science. 33(2):255-267.

Brissette, John C. 1990. Root growth, root function, and water relations of shortleaf pine (Pinus echinata Mill.) bare-root seedlings transplanted into different edaphic environments. Baton Rouge: Louisiana State University. 135 p. Ph.D. dissertation.

Brissette, John C.; Barnett, James P.; Gramling, Charles L. 1989a. Root growth potential of southern pine seedlings grown at the W. W. Ashe nursery. In: Proceedings, southern forest nursery association; 1988 July 25-28; Charleston, SC. Columbia, SC: South Carolina Forestry Commission: 173-183.

Brissette, John C.; Carlson, William C. 1987a. Effects of nursery density on shortleaf pine. In: Landis, Thomas D. compl. Meeting the challenge of the nineties: proceedings, intermountain forest nursery association; 1987 August 10-14; Oklahoma City, OK. Gen. Tech. Rep. RM-151. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 36-41.

Brissette, John C.; Carlson, William C. 1987b. Effects of nursery bed density and fertilization on the morphology, nutrient status, and root growth potential of shortleaf pine seedlings. In: Phillips, Douglas R., ed. Proceedings, fourth biennial southern silvicultural research conference; 1986 November 4-6; Atlanta, GA. Gen. Tech. Rep. SE-42. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 198-205.

Brissette, John C.; Roberts, Terrence C. 1984. Seedling size and lifting date effects on root growth potential of loblolly pine from two Arkansas nurseries. Tree Planters' Notes 35(1):34-38.

Brissette, John C.; Tiarks, Allan E.; Carlson, William C. 1989b. Comparing the effects of equal versus increasing application rates of nitrogen on the quality of shortleaf pine seedlings. In: Miller, James H., ed. Proceedings, fifth biennial southern silvicultural research conference; 1988 November 1-3; Memphis, TN. Gen. Tech. Rep. SO-74. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 95-105.

Carlson, W. C. 1985. Effects of natural chilling and cold storage on budbreak and root growth potential of loblolly pine (Pinus taeda L.). Canadian Journal of Forest Research. 15(4):651-656.

Carlson, W. C. 1986. Root system considerations in the quality of loblolly pine seedlings. Southern Journal of Applied Forestry. 10(2):87-92.

Chung, Hsu-Ho; Kramer, Paul J. 1975. Absorption of water and ^{32}P through suberized and unsuberized roots of loblolly pine. Canadian Journal of Forest Research. 5:229-235.

DeWald, Laura E.; Feret, Peter P. 1988. Changes in loblolly pine seedling root growth potential, dry weight, and dormancy during cold storage. Forest Science. 34(1):41-54.

Dierauf, T. A.; Olinger, H. L. 1982. Loblolly pine undercutting, lateral root pruning, and top clipping study. Charlottesville, VA: Virginia Division of Forestry; Occasional Report 58. 6 p.

Duryea, Mary L. 1990. Nursery fertilization and top pruning of slash pine seedlings. Southern Journal of Applied Forestry. 14(2):73-76.

Feret, Peter P.; Kreh, Richard. 1986. Effect of undercutting on loblolly pine seedling size and its relation to root growth potential. Southern Journal of Applied Forestry. 10:24-27.

Fowells, Harry A.; Krauss, Robert W. 1959. The inorganic nutrition of loblolly pine and Virginia pine with special reference to nitrogen and phosphorus. Forest Science. 5(1):95-112.

Garber, Melvin, P.; Mexal, John G. 1980. Lift and storage practices: their impact on successful establishment of southern pine plantations. New Zealand Journal of Forestry Science 10(1):72-82.

Garner, J. W.; Dierauf, T. A. 1976. Changes in loblolly pine seedling dry weight and top to root ratio between October and March. Charlottesville, VA: Virginia Division of Forestry; Occasional Report 50. 3 p.

Hallgren, S. W.; Tauer, C. G. 1989. Root growth potential, first-year survival, and growth of shortleaf pine seedlings show effects of lift date, storage, and family. Southern Journal of Applied Forestry. 13(4):163-169.

Hatchell; Glyndon E. 1985. Nursery cultural practices affect field performance of longleaf pine. In: South, David B. ed. Proceedings, international symposium on nursery management practices for the southern pines; 1985 August 4-9; Montgomery, AL. Auburn, AL: Auburn University: 148-156.

Hennessey, T. C.; Dougherty, P. M. 1984. Characterization of the internal water relations of loblolly pine seedlings in response to nursery cultural treatments: implications for reforestation success. In: Duryea, Mary L.; Brown, Gregory N. eds. Seedling physiology and reforestation success. Dordrecht/Boston/London: Martinus Nijhoff/Dr W. Junk Publishers: chapter 10.

Hinesley, L. Eric; Maki, T. E. 1980. Fall fertilization helps longleaf pine nursery stock. Southern Journal of Applied Forestry. 4(3):132-135.

Huberman, M. A. 1940. Normal growth and development of southern pine seedlings in the nursery. Ecology 21(3):323-334.

Hunt, Roderick; Nicholls, A. 0. 1986. Stress and the coarse control of growth and root-shoot partitioning in herbaceous plants. Oikos 47(2):149-158.

Kormanik, Paul P. 1989. Frequency distribution of first-order lateral roots in forest tree seedlings: silvicultural implications. In: Miller, James H., ed. Proceedings, fifth biennial southern silvicultural research conference; 1988 November 1-3; Memphis, TN. Gen. Tech. Rep. SO-74. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 101-105.

McGee, Charles E. 1963. A nutritional study of slash pine seedlings grown in sand culture. Forest Science. 9(4):461-469.

Mexal, John G. 1981. Seedling bed density influences seedling yield and performance. In: Lantz, Clark W. ed. Proceedings, southern nursery conference; 1980 September 2-4; Lake Barkley, KY. Tech. Pub. SA-TP17. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southeaster Area: 89-95.

Nambiar, E. K. Sadanandan. 1980. Root configuration and root regeneration in Pinus radiata seedlings. New Zealand Journal of Forestry Science. 10(1):249-263.

Nebgen, Russell J; Meyer, Joann F. 1985. Seed bed density, undercutting, and lateral root pruning effects on loblolly pine seedling morphology, field survival, and growth. In: South, David B. ed. Proceedings, international symposium on nursery management practices for the southern pines; 1985 August 4-9; Montgomery, AL. Auburn, AL: Auburn University: 136-147.

Orlander, G. 1986. Effect of planting and scarification on the water relations in planted seedlings of Scots pine. Studia Forestalia Suecia 173. 17 p.

Rietveld, W. J. 1989. Transplanting stress in bareroot conifer seedlings: its development and progression to establishment. Northern Journal of Applied Forestry 6:99-107.

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(1):218-248.

Rowan, Samuel J. 1985. Seedbed density affects performance of slash and loblolly pine in Georgia. In: South, David B. ed. Proceedings, international symposium on nursery management practices for the southern pines; 1985 August 4-9; Montgomery, AL. Auburn, AL: Auburn University: 126-135.

Sands, R.; Fiscus, E. L.; Reid, C. P. P. 1982. Hydraulic properties of pine and bean roots with varying degrees of suberization, vascular differentiation and mycorrhizal infection. Australian Journal of Plant Physiology 9:559-569.

Shoulders, Eugene. 1965. Root pruning in southern pine nurseries. Tree Planters' Notes. No. 70:12-15.

South, David B.; Larsen, Harry S.; Williams, Hans M.; Boyer, James N. 1989. Use of seedling size as a covariate for root growth potential studies. In: Miller, James H., ed. Proceedings, fifth biennial southern silvicultural research conference; 1988 November 1-3; Memphis, TN. Gen. Tech. Rep. SO-74. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 89-93.

Switzer, G. L.; Nelson, L. E. 1963. Effects of nursery fertility and density on seedling characteristics, yield, and field performance of loblolly pine (Pinus taeda L.). Soil Science Society Proceedings. 27:461-464.

Tanaka, Yasuomi; Walstad, J. D.; Borrecco, J. E. 1976. The effect of wrenching on morphology and field performance of Douglas fir and loblolly pine seedlings. Canadian Journal of Forest Research. 6:453-458.

Timmer, V. R.; Armstrong, G. 1987. Growth and nutrition of containerized Pinus resinosa at exponentially increasing nutrient additions. Canadian Journal of Forest Research. 17:644-647.

Venator, Charles R.; Mexal, John G. 1981. The effect of wrenching and planting date on the survival of loblolly pine seedlings. In: Barnett, James P., ed. Proceedings, first biennial southern silvicultural research conference; 1980 November 6-7; Atlanta, GA. Gen. Tech. Rep. SO-34. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 20-28.

Wakeley, Philip C. 1954. Planting the southern pines. U.S. Department of Agriculture Monograph No. 18. 233 p.

Williams, Hans M.; South, David B.; Webb, Alan. 1988. Effects of fall irrigation on morphology and root growth potential of loblolly pine seedlings growing in sand, South African Forestry Journal. 147:1-5.

Zimmermann, Martin H.; Brown, Claud L. 1971. Trees structure and function. New York: Springer-Verlag. 336 p.