Vegetative Propagation of Rocky Mountain Douglas-fir by Stem Cuttings

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*In October 1985, stem cuttings collected from 6,828 five-year-old Douglas-fir (*Pseudotsuga menziesii *var.* glauca *(Beissn.) Franco) of 457 families in 9 progeny test plantations in northern Idaho were treated and stuck for rooting in nursery mix in cells in a Coeur d'Alene nursery mist chamber. Tops were kept cool and the rooting zone warm. After 120 days the growing regime was gradually changed to a standard container rearing regime. Overall, 62% of the clones successfully rooted; 98.5% of the families rooted. Success was related to the condition of the ortet. The rooted cuttings were outplanted to two sites in northern Idaho in 1987. Survival was greater than 95% for the first two growing seasons at both sites. Plagiotropism was largely outgrown by the end of the second growing season at the more favorable site (a nursery transplant bed).* Tree Planters' Notes 41(3): 3 - 6 ; 1990.

Vegetative propagation has long been employed in tree improvement programs, principally in the form of grafting. Much attention has been focused on the promise of tissue culture but considerable development is still necessary before the promise can be fulfilled.

Rooted cuttings are a third form of vegetative propagation, and the one this paper considers. Vegetative propagation is beneficial for several reasons. Most importantly, the genotype of the ortet is transferred to the ramet (the ortet is the donor tree; the ramet is the cutting; all genetically identical plants are members of the same clone).

Rooting of woody plant cuttings has been discussed in books on propagation and in special review articles. These reviews clearly show that the anatomical and physiological conditions of the cuttings at the time of collection, before they are set out for rooting and during the rooting period, will affect their rooting behavior. The procedures involved from selection of cuttings to treatments of the rooted cuttings are discussed.

Rooted cuttings allow the production of large numbers of plants from genetically improved seedlots that are too limited to allow the use of normal nursery techniques for planting stock production. Cuttings of this type have foliage and must be rooted under moisture conditions that will prevent excessive drying, as they are usually slow to root, taking several months to a year. There is considerable variation among the different species within a genus. Cuttings taken from young ortets (< 10 years) root much more readily than those taken from older ortets. Treatments with root-promoting substances, particularly indolebutyric acid at relatively high concentrations, are usually beneficial in increasing the speed of rooting and the percentage of cuttings rooted and in obtaining heavier root systems.

Cuttings of evergreen conifers ordinarily are best taken between late fall and late winter. Rapid handling of the cuttings after the material is taken from the ortets is important. The cuttings are best rooted in a greenhouse with a relatively high light intensity and under conditions of high humidity or very light misting but without heavy wetting of the leaves. A bottom heat of 75 to 80 °F has shown good results. Mature terminal shoots of the previous season's growth are usually used. Cuttings are typically 4 to 8 inches long, with all the foliage removed from the lower half of the cutting.

Materials and Methods

Materials and timing. The ortets for this project were trees (of seed origin) in nine progeny test plantations in northern Idaho. The ortets were 5 years old (from seed) when ramets were collected in the fall of 1985. About 7 dormant laterals (1985 growth only) were snipped with pruning shears from selected trees in each of 457 families in the nine plantations. Cuttings were collected from a total of 6,828 trees.

The cuttings from each tree were immediately tagged and sealed along with wet paper toweling in a zipper-lock plastic sandwich bag, and delivered to the Forest Service

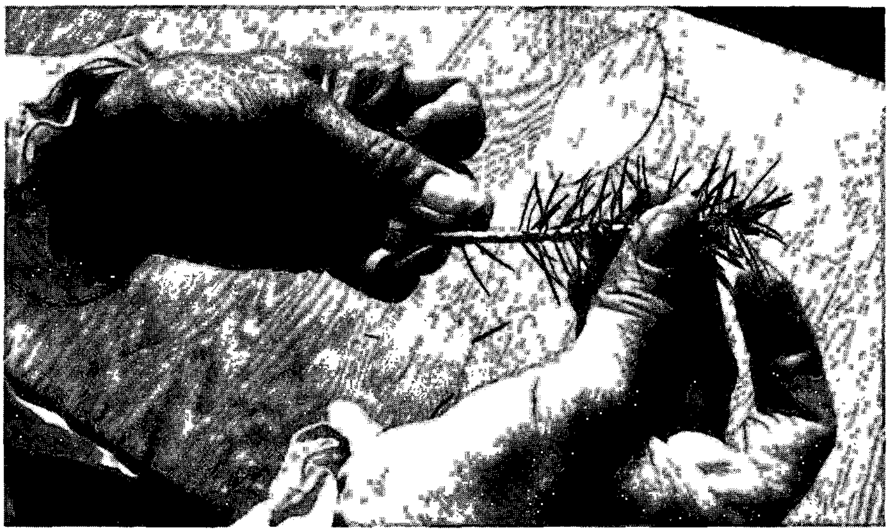

Figure 1—*Removing lower needles from cutting.*

Coeur d'Alene (Idaho) Nursery for rooting. Collectors had been instructed to collect cuttings that were a minimum of 6 inches long.

Based on previous experiments, all cuttings were collected starting the last week of October. The cuttings from the last plantation arrived at the nursery in mid-November.

Hormone treatment. Cuttings were processed and stuck as quickly as possible—no interim cold storage. Due to the poor quality of the current season's growth, the 6-inch minimum was waived. Needles were stripped from the basal third to half of the length to facilitate chemical treatment and insertion of the cuttings into the rooting medium (fig. 1). A healthy, intact terminal bud was a prerequisite to inclusion of the cutting in the program.

The basal end of each ramet was cut on the diagonal prior to hormone treatment (fig. 2). The stripped basal end was dipped in Hormidin No. 3 (MSD Agvet, Rahway, NJ), which is 0.8% IBA, active ingredient (fig. 3).

Rooting medium and container. From our previous studies, a forest nursery mix containing 50% vermiculite and 50% sphagnum peat moss was selected as the rooting medium. This material seemed to provide a good compromise of proper drainage and necessary water and nutrient-holding ability. The top one-half to three-fourths inch was filled with perlite to help inhibit growth of moss and algae. The container itself was a Ray Leach Super Cell, a 10-cubic-inch individual container. The advantage of individual cells is that dead or diseased material can be removed without affecting surrounding plants. A nail was used to form a planting spot so that the rooting hormone would not be rubbed off when the cutting was inserted into the rooting medium.

Propagation structure and environment. A standard double-layer quonset design greenhouse covered with two sheets of Monsanto Cloud 9 (Monsanto Co., Kearny, NJ), formed the basic structure. Inside the house, a concrete floor, block supports, and metal benches were used to support the containers in a manner to facilitate sanitation. Benches were four trays wide, with a mist line running down the center of each bench. Deflector-type spray nozzles were inserted in the lines. The mist system was divided into four zones to allow for maximum uniformity. The heating, cooling, and ventilation equipment was controlled by an Acme Growtron Controller (Acme Engineering, Muskogee, OK).

To avoid excessive desiccation of sticklings (the cuttings stuck in the rooting medium), both the rooting medium and the air were kept at high humidity by a soaking mist that was applied for 1 minute every hour during daylight. At night, the mist was applied once at midnight to avoid desiccation from the heaters. By starting the process in late fall and having the heat tubes running under the bench, the sticklings were maintained with a warm

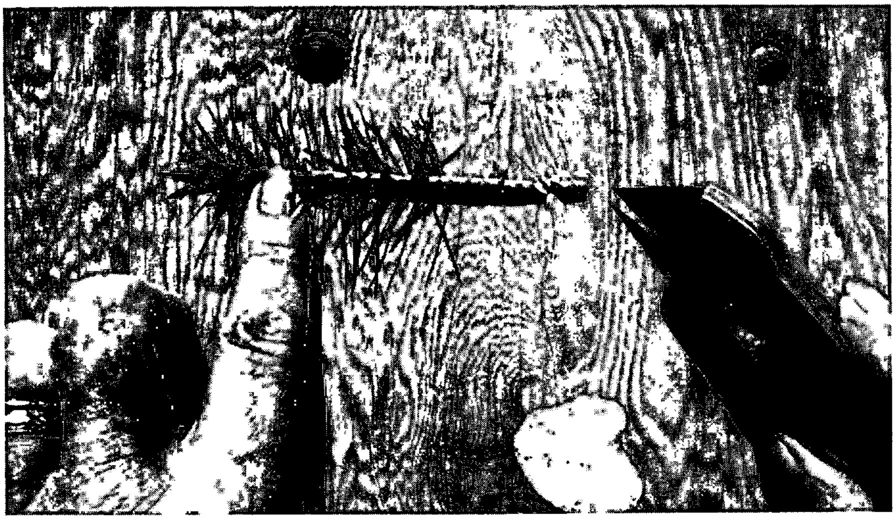

Figure 2—*Making the diagonal cut on the base of the cutting before hormone treatment.*

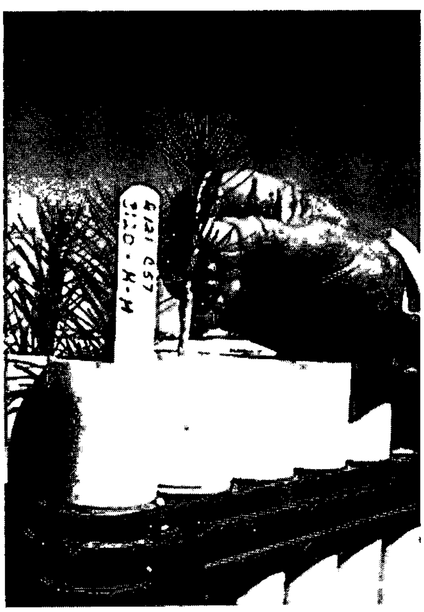

Figure 3—*Cutting immediately after dipping basal end in rooting compound.*

rooting medium and cool tops. Air temperature at plant height was 63 to 68 °F. No supplemental lighting was used during the rooting process. The sticklings were held in this environment for 120 days.

At the end of 120 days, misting was gradually reduced and the sticklings were placed on a seedling growing regime. This regime started with low nitrogen and high potassium and phosphorus levels. After 45 days, N levels were increased and P and K levels reduced. The first N level provided for root growth while the latter provided for top growth. Terminal buds began to elongate in late March and early April. We found that sticklings that successfully flushed had rooted.

Rooting Percentages and Variation Among Trees

In all, 45,219 cuttings were stuck. Of those, 18,215 rooted (table 1). This was a 40.3% success ratio. Short cutting length, poor vigor, and small bud size played a significant role in those sticklings which did not root. Family rootability ranged from 0 to 91.4%. The rate of rooting for the sticklings from the nine donor progeny test plantations ranged from 33 to 85%.

Outplantings

All healthy rooted cuttings were planted in the spring of 1987 at two sites in northern Idaho. The most vigorous of the trees were planted at the Dry Creek Tree Improvement Area near Clark Fork; the remainder were planted in a transplant bed at the Coeur d'Alene Nursery. Both plantings enjoyed high survival (> 95%) in the first two growing seasons.

At the time of planting, virtually all the rooted cuttings exhibited strong plagiotropic growth (the

Table 1—*Rooting success*

	Number	Percent
Families collected	457	—
Families producing rooted sticklings	450	98.5
Ortets collected	6,828	—
Clones represented by 2 or more ramets	4,234	62
Clones represented by 0 or 1 rooted	2,594	38

tendency to grow laterally, like branches), which persisted through the first growing season (1987) at both sites. By the middle of the 1988 growing season, we estimated that > 90% of the trees in the nursery transplant bed were growing strongly orthotropically (that is, tending to grow erect). Those at Dry Creek were less orthotropic even though the latter had been more vigorous when planted. Irrigation, nutrition, and weed control probably accounted for the differences in overcoming plagiotropism. The trees at the nursery were more frequently irrigated, fertilized, and weeded. These trees were also generally larger and more vigorous after two growing seasons.

Summary

A great variety of factors affect the rooting of Rocky Mountain Douglas-fir cuttings. The vigor of the ortet plays a significant role. Our impression was that the greatest factor in the success of rooting was the apparent vigor of the cuttings. The 1985 growing season had been quite droughty and many of the trees had produced only very short lateral shoots with sparse, short needles. The preponderance of rooting failures were in these cuttings.

The individual genetic makeup of the clone cannot be discounted. The handling between the time of collection and subsequent treatment is also a factor. Having the right facilities and managing them properly are essential. In addition to bottom heat and cooler air temperatures, it is critical that proper humidity be maintained, as well as good air circulation. Plagiotropic growth can easily contribute to the spread of disease problems. The procedures described in this report have now proven themselves using material from a wide variety of sources.

Plagiotropism in rooted cuttings from young ortets apparently can be expected to be largely outgrown in two growing seasons under good cultural conditions. If such conditions cannot be provided in the outplanting, the growers and users of rooted cutting should consider growing the trees for 1 year (or 2) in nursery transplant beds where appropriate treatments can be administered.

Effect of Nursery-Produced Endomycorrhizal Inoculum on Growth of Redwood Seedlings in Fumigated Soil

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Inoculation of fumigated nursery bed soil with spores of Glomus mosseae *(Nicolson & Gerdemann) Gerdemann & Trappe greatly increased growth of redwood (*Sequoia sempervirens *(D. Don) Endl.) seedlings over non-inoculated seedlings. Nursery production and use of endomycorrhizal inoculum are discussed.* Tree Planters' Notes 40(3): 7 -11; 1990.

Mycorrhizae form an important symbiotic relationship with their hosts' roots; neither host nor fungus are likely to survive alone. Endomycorrhizal fungi, also called **vesicular-arbuscular mycorrhizae** (VAM), are ubiquitous fungi found throughout the world on more than 1,000 genera of higher plants *(19)*, including grasses *(13)*, hardwoods *(8, 18)*, and conifers *(7, 9)*.

Endomycorrhizae occur naturally on roots of redwood (*Sequoia sempervirens* (D. Don) Endl.) and giant sequoia (*Sequoiadendron giganteum* (Lindl.) Buchh.) in California forests *(9)*. *Glomus mosseae* (Nicolson & Gerdemann) Gerdemann & Trappe occurs naturally in the soil of Ben Lomond State Forest Nursery, located at Ben Lomond, CA.

Because the common nursery practice *(10)* of soil fumigation greatly reduces VAM populations in nursery beds, reintroduction of VAM before seeding is imperative for achieving acceptable levels of seedling survival and growth *(8, 18)*. Inoculation of fumigated beds with VAM or planting VAM-colonized seedlings in fumigated soil results in normal growth of hardwood seedlings *(8, 10, 18)*. Hardwood seedling inoculation has been accomplished by transferring inoculum-bearing soil from forest sites to the nursery *(18)*, by transferring inoculum-bearing soil grown on an intermediate crop in the greenhouse *(11)*, and by growing colonized cover crops in the seedbed the year before hardwood seeds are sown *(5, 8)*.

Early colonization of young seedling roots occurs via the applied inoculum. Later, more extensive root colonization occurs as a result of inoculation from nearby earlier colonized roots *(17)*. No attention has been given to developing procedures for large-scale inoculation of conifers dependent upon VAM.

Powell *(16)* reviewed field inoculation procedures for many annual and perennial crop plants. Kough *et al. (7)* demonstrated an early growth response of endomycorrhizae-inoculated redwoods and other members of the Taxodiaceae and Cupressaceae in plastic growth tubes. Menge *(12)* comprehensively reviewed inoculum production and storage technology for endomycorrhizal pot cultures. Sudan grass (*Sorghum sudanense* (Piper) Stapf) was found to support endomycorrhizal fungi, including *G. mosseae (1, 3, 4)*.

Bareroot redwood seedlings grown on fumigated, non-inoculated soil at Ben Lomond State Nursery were nonmycorrhizal, stunted, and off-color, and frequently failed to survive. This report investigates the utility of sudan grass and 2+0 redwood for production of *G. mosseae* inoculum to inoculate fumigated nursery beds and describes an efficient and practical inoculation procedure. The study was carried out at the Ben Lomond State Forest Nursery near Santa Cruz on the central California coast.

Methods

Laboratory. *Spore extraction from soil.* To ensure cost-efficient use of valuable nursery bed space

The authors thank J. Menge, the University of California—Riverside, for identifying the mycorrhiza.

and labor, it was necessary to determine spore numbers of *G. mosseae* in the inoculum-soil. The assay procedure involved two steps: extracting spores from a sample of the inoculum-soil and counting spores in that sample. All assays were replicated three times for each soil.

Ten fifty-milliliter samples of soil were collected from redwood production beds (RPB) and sudan grass beds (SGB) and combined for each inoculum source. The number of *G. mosseae* spores per milliliter of soil was determined by using a firmly packed 25-ml soil subsample taken from each of the combined soil collections. Using the sieving method of Gerdemann and Nicolson *(6)*, each soil sample was gently washed through soil sieves stacked from the top down in the following order: mesh openings of 250 μm (for collection and removal of debris) and of 150, 106, and 53 μm respectively (for spore collection). Although the majority of the spores were collected on the 106-μm sieve, small quantities of spores were also collected on the 150- and 53-μm sieves. These three collections containing spores and soil were combined by washing onto the screen of a small-diameter, 25-μm soil sieve.

Spore numbers assay. Spores of *G. mosseae* are not readily decanted free of similar sized soil particles because the spores sink rather than float in water. For this reason the usual method of decanting *(6)* could not be used and the following spore recovery method was devised. Two-hundred and fifty milliliters of a 35% sucrose solution was carefully layered beneath 150 ml of distilled water in a 500-ml graduated glass cylinder. Congo red stain was previously added to the sucrose solution to make the sucrose-water interface visible. The combined sieved soil collection was gently rinsed with distilled water down the inner surface of the graduated cylinder and allowed to settle for 20 minutes. Spores of *G. mosseae* were collected by pipette from the upper region of the sucrose solution.

Collections were prepared for spore counting by using vacuum filtration. The filtration system consisted of a 0.45-μm, 47-mm Gelman Gn-6 gridded filter membrane seated in a 115-ml Nalgene disposable analytical filter unit, to which a vacuum pump was attached. While a vacuum of less than 250 mm Hg was applied, the spore suspension in the pipette was slowly dispersed over the filter membrane. Spore collection from the graduated cylinder was repeated as necessary to recover all spores. Spores of *G. mosseae* were identified and counted with a microscope at 20 to 40× power. Assays were replicated three times to estimate the number of spores per milliliter contained in the inoculum-soil.

Field. *Inoculum collection and preparation.* Inoculum from the redwood production beds came from recently harvested 2+0 beds, and inoculum from sudan grass beds came from beds seeded 1 year earlier. Both RPB and SGB soils containing spores of *G. mosseae* were collected 8 weeks before use (immediately after harvest of the 2+0 RPB beds) from the top 6 inches of the bed. These soils were air dried (< 20 °C) on heavy paper, sieved (1/8-inch mesh) to remove debris, and stored at temperatures below 20 °C in 4×4×3-foot wooden boxes in an enclosed area.

Seed bed preparation, inoculation, sowing, and care. Test beds were fumigated 2 weeks before inoculation with 175 pounds per acre methyl bromide (57%) and chloropicrin (43%). Bed plots were laid out according to a randomized block design. Four 4 × 50-foot replicates were used for each of the three treatments: non-inoculated control, inoculum from RPB, and inoculum from SGB. Inoculum-soil containing spores of *G. mosseae* was used to inoculate the test beds according to the experimental design and rates: 0 spores/ft^2 = controls and 100 spores/ft^2 = inoculated.

Soil samples from RPB and SGB beds containing spores of *G. mosseae* were incorporated into the prepared beds with a fertilizer drill set to place the inoculum at a depth of 0.5 to 2.0 inches (12 to 50 mm). Drill spacing was set to approximate the seed drill spacing of eight rows within a 4-foot-wide bed. Inoculation rates were calibrated into the fertilizer drill to provide about 50 spores/ft^2 for each inoculum source. To ensure good dispersal of spore inoculum at a final rate of 100 spores/ft^2, the inoculum was drilled into the bed in two passes in opposite directions.

Inoculum drilling was followed immediately by seed drilling. Upgraded seed from the L.A. Moran Reforestation Center (lot 4750, Humboldt County source, 65% lab germination rate) was drilled into the top 4 to 6 mm of the bed with a Love seed drill, set to achieve a seedling density of 25/ft^2. All seed beds were irrigated immediately after sowing to a depth beyond inoculum placement. Beds were irrigated thereafter as needed to maintain moisture in the root area.

Data collection. Seedling height and caliper were measured at the end of the first and second growing seasons, except that height measurements were not taken on seedlings of treatment groups requiring top pruning during the second year. Caliper was measured immediately beneath the basal bud whorl at the top of the hypocotyl. Roots of seedlings from each treatment were examined microscopically (cleared and stained) at the end of both growing seasons for mycorrhizae *(2, 14).*

Results and Discussion

Adequate inoculum levels were reflected in the uniform growth of seedlings grown in inoculated beds. Inoculum source bed spore numbers varied with the host: RPB soil yielded about 1 spore/ml, SGB soil about 0.2 spores/ml. These numbers may seem low when compared with spore counts from soil of other endomycorrhizal fungi. However, spores of *G. mosseae* are large and have a high nutrient reserve that potentially allows several germinations and produces hyphae that can "explore" soil area for host roots (John Menge, personal communication).

Seedlings from the non-inoculated beds did not meet nursery standards at the end of the second year and were culled. All seedlings from the inoculated beds were top-pruned after the first year to keep height within nursery standards. There were no differences in plant growth between the inoculum sources (RPB and SGB) (table 1). Non-inoculated seedlings were significantly shorter in height and smaller in caliper than inoculated seedlings at the end of both the first and second growing seasons. Nearly all seedlings in the inoculated beds were mycorrhizal at the end of the first year. As a result of natural dispersal of VAM, a few seedlings in non-inoculated beds became mycorrhizal by the end of the first year, and a few more were mycorrhizal by the end of the second year.

Natural reintroduction of endomycorrhizal fungi into fumigated soil at Ben Lomond State Nursery occurs over time. We observed that seedlings growing along small surface watercourses in fumigated but non-inoculated beds were noticeably larger than nearby seedlings, in the same bed, that were not associated with these drainages. Evidently, VAM inoculum (spores and possibly hyphal fragments) from non-fumigated adjacent beds was carried to the fumigated beds during periods of heavy rain or irrigation. Very likely, inoculum moves along with soil during ripping, discing, and leveling operations. Spores also are dispersed naturally by wind *(21)* and by animals, which ingest spores (in sporocarps) and pass them through their digestive tracts *(15, 20, 21).*

Spores of *G. mosseae* appear to be particularly susceptible to damage under conditions of desiccation or excessive heat (Adams, unpublished data). Because seed beds are dry in preparation for sowing, conditions in these beds may not be

Table 1—*Mean caliper and height of redwood seedlings inoculated with* Glomus mosseae *from two sources*

Measurement and growth year	Inoculum source RPB	Inoculum source SGB	Non-inoculated control
Caliper (mm)*			
1	3.8 a	3.7 a	1.5 b
2	6.5 a	6.9 a	3.2 b
Stem height (cm)			
1	27.8 a	29.1 a	6.5 b
2	NA	NA	16.3

*Measurements of hypocotyl diameter were taken immediately below basal bud whorl.

Means within a row (year) followed by the same letter do not differ at P = 0.01 (Duncan's multiple range test). RPB = redwood production bed, SGB = Sudan grass bed. NA = not available; RPB and SGB seedlings were topped during the second growing season.

favorable for spore survival. Therefore, it is imperative that the inoculated soil be irrigated immediately after sowing to avoid any loss of inoculum due to desiccation or excessively high temperatures.

Giant sequoia and incense-cedar (*Libocedrus decurrens* Torr.), both endomycorrhizal hosts, were inoculated at the same time as the redwood. The response of these hosts to inoculation closely paralleled that of redwood.

Sudan grass was to be grown each year specifically as a host crop for spore production and would be inoculated with RPB soil. However, although spores were produced, their relatively low numbers (compared to the RPB source) necessitated far too much soil collection and handling to be cost efficient. To meet time schedules and availability of personnel at the Ben Lomond State Nursery, soil inoculation methods must be easily performed and offer cost-effective benefits. Handling of inoculum (harvest, storage, preparation, and soil inoculation) must be manageable by nursery personnel and equipment without undue expenditure of time and equipment. The procedure described here meets the nursery's needs for dependable growth of quality seedlings. It is also noteworthy to point out that no disease problems have occurred over the subsequent years that RPB soil has been used.

Summary

Glomus mosseae is a very useful mycorrhizal fungus for colonization of redwood seedlings in fumigated nursery beds and appears to be equally useful with seedlings of giant sequoia and incense-cedar. Inoculum is readily and easily produced in "working" nursery beds. However, care must be taken to protect the inoculum from drying or heating at any time from collection through seedbed irrigation. Disease development must be closely monitored.

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Lime-Amended Growing Medium Causes Seedling Growth Distortions

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Although a commercial growing medium with incorporated agricultural lime had been successfully used for years, it caused growth distortion of coniferous and deciduous seedlings during 1988. Seedlings grown in the amended medium were stunted and chlorotic, often with disfigured needles and multiple tops. Seedlings grown in the same medium without incorporated lime grew normally. These symptoms are attributed to a nutritional problem caused by dolomitic limestone in the medium. Tree Planters' Notes 41(3):12-17; 1990.

Dolomitic limestone is commonly added to commercial growing media, usually to raise pH and serve as a source of calcium (Ca) and magnesium (Mg). Four container nurseries in northern Idaho had been using the same peat-vermiculite (1:1) growing medium with incorporated limestone for several years, with good to excellent results. However, distorted Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) seedlings were occasionally observed. Although the number of distorted seedlings was never widespread or serious, much speculation was given to the cause. In 1988, however, serious problems developed.

Contribution 518 of the Idaho Forest, Wildlife, and Range Experiment Station.

The Problem

Three weeks after germination was complete, portions of the crop were obviously chlorotic and stunted. The problem was unusual because it often affected every tree in a particular block (either pine cell tray or Styrofoam block), but not every block in a given seedlot. Affected blocks were randomly distributed throughout the seedlot. Eleven coniferous and 3 hardwood species appeared affected, although Douglas-fir and spruce (*Picea*) spp. were the most severely affected (table 1). The severity of the problem also varied with seedlot.

As the seedlings matured, the pine species recovered somewhat after being given additional nitrogen, although they were still shorter than normal seedlings. The symptoms of the Douglas-fir, western larch, grand fir, and spruce seedlings became more acute, often resembling herbicide damage. A club-like swelling also formed just beneath the terminal bud (fig. 1). These seedlings remained chlorotic and stunted, with

Table 1—*Species affected by lime-amended growing medium*

Common name	Scientific name
Conifers	
Rocky Mountain Douglas-fir	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco
Engelmann spruce	*Picea engelmannii* Parry ex Engelm.
Blue spruce	*Picea pungens* Engelm.
Norway spruce	*Picea abies* (L.) Karst.
Western larch	*Larix occidentalis* Nutt.
Western redcedar	*Thuja plicata* Donn ex D.Don
Western white pine	*Pinus monticola* Dougl. ex D.Don
Ponderosa pine	*Pinus ponderosa* Dougl. ex Laws.
Scotch pine	*Pinus sylvestris* L.
Austrian pine	*Pinus nigra* Arnold
Grand fir	*Abies grandis* (Dougl. ex D.Don) Lindl.
Hardwoods	
Chokecherry	*Prunus virginiana* L.
Nanking cherry	*Prunus tomentosa* Thunb.
River birch	*Betula nigra* L.

Figure 1—*Douglas-fir seedling with tight curling of needles, resembling herbicide damage.* ***Arrow*** *points to swelling beneath the terminal bud.*

Figure 2—*A 6-month-old Douglas-fir with little internodal extension (circular object is camera lens cover).*

very short needles and deformed terminal buds. Some affected seedlings had extremely small internodes, and many 6-month-old seedlings were only 3 to 4 cm tall (fig. 2). The most severely stunted seedlings eventually developed tip necrosis (fig. 3). Some affected seedlings seemed to lose apical dominance as the lateral shoots continued to grow, often resulting in seedlings with multiple tops (fig. 4). The root systems were apparently unaffected, and most distorted seedlings had firm root plugs.

This problem was frustrating because an exact cause could not be identified. Assays for pathogenic fungi were negative. The pH of the medium was determined before sowing and ranged from 4.4 to 4.5. Three weeks after symptoms appeared, pH measurements of trays of normal looking seedlings and stunted seedlings were very similar, 6.7 and 6.8 respectively, although these values were higher than the target pH range (5.8 to 6.0).

Seedling tissue samples were analyzed at 12 weeks after germination to check for mineral nutrient deficiency or toxicity; the results were inconclusive (table 2). Even though irrigation water was acidified, further acidification of the water did not relieve the problem. Finally, late in the season, repeated applications of high rates of ammonium nitrate relieved the problem in some of the affected seedlings, but unfortunately allowed normal seedlings to grow too tall.

The Study

In 1988, four nurseries in northern Idaho and another in western Montana participated in a cooperative research project not originally intended to examine the effects of limestone-amended media. One batch of growing medium with incorporated dolomitic limestone was divided and samples were sent to participating nurseries. At the northern Idaho nurseries, Douglas-fir seedlings were grown in dolomite-amended media, but at the Montana nursery, two Douglas-fir seedlots were sown into cells containing growing medium with dolomitic limestone and growing medium without limestone.

Figure 3—*Apical necrosis of a distorted Douglas-fir seedling.*

At the Montana nursery, 90% of the trees grown under the nursery's usual regime in medium with dolomitic limestone were stunted (fig. 5). Normal seedlings were significantly taller, but the root collar diameters (calipers) of both normal and symptomatic seedlings were similar (table 3).

Of the five nurseries participating in the study, only the western Montana nursery and one northern Idaho nursery reported widespread stunting of Douglas-fir seedlings in medium with incorporated dolomite.

The Analysis

Although an exact reason for the growth problems may never be verified experimentally, we believe that the symptoms were caused, either directly or indirectly, by dolomitic limestone in the growing medium, probably by uneven incorporation of the dolomite. Problems with incorporated fertilizers are not unusual; Whitcomb concluded that variable growth of container nursery stock was mostly due to improper mixing of incorporated fertilizers *(13)*. This is even more of a problem in the small-volume containers used in forest nurseries, as it is difficult to evenly distribute a charge of fertilizer to each cell *(7)*. Even in a well-mixed medium, the amount of fertilizer can vary drastically because dry incorporated amendments easily separate out from dry growing medium during handling *(1)*.

Although the pH of the growing medium with incorporated dolomite was high, pH alone may not have been the root of the problem. Whitcomb concludes that nutrition of container-grown plants is unaffected by pH, and micronutrients are readily available between pH 4.0 and 7.0 *(12)*. However, when high concentrations of Ca, Mg, sodium (Na), or bicarbonates are present, micronutrient nutrition of container-grown plants is affected.

The symptoms were probably related to a mineral nutrient deficiency or toxicity. Affected seedlings had chlorotic terminal leaves, necrotic growing tips, short internodal distance and misshaped needles—these are common symptoms of boron (B), Ca, and copper (Cu) deficiency *(9)*. A Ca deficiency seems unlikely, because the pH of medium supporting affected seedlings was high and distortion was noted only in medium with incorporated calcium and magnesium, but a Ca "toxicity" is a possibility (Landis 1988). Also, the ratio of Ca and Mg must be balanced to prevent Mg or Ca deficiencies *(13)*.

Copper levels are inherently low in soils with high organic matter contents, and the dolomite may have further reduced Cu availability *(8)*. Maintaining the high organic growing medium in a saturated condition may also induce Cu deficiency. Because seedlings in both media were watered the same and foliar levels were similar, this seems unlikely as the source of the problem, although later irrigations to the less rapidly growing, stunted seedlings may have affected Cu availability.

Figure 4—*Douglas-fir seedling exhibiting a lack of apical dominance but continued growth of lateral branches.*

Boron deficiency is commonly induced by liming acid soils. Soils with high levels of Ca and a pH greater than 6.5 can show B deficiency *(4)*. Even though tissue analysis did not show an apparent deficiency, the ratio of Ca to B may have been outside the range for normal plant growth *(11)*.

Stevenson *(11)* reports excessive plant uptake of Ca supplied by lime may cause a nutrient imbalance in the plant, and Brown *(2)* speculates iron (Fe) chlorosis is one such example. In fact, dolomitic limestone incorporated into a peat-vermiculite growing medium has been shown to induce lime chlorosis in Douglas-fir seedlings *(3)*. Landis' review *(5)* indictates that chlorotic plants with an iron deficiency are characterized by more total Fe and total Ca in their tissue than normal seedlings. Our tissue analysis data (table 2) shows distorted seedlings did indeed have higher amounts of Ca and Fe than normal seedlings.

Table 2—*Tissue analysis of distorted and healthy appearing Douglas-fir seedlings during budset in the growth cycle*

	Healthy	Distorted	Standard*
Macronutrients (%)			
N	0.93	2.31	1.40–2.20
P	0.31	0.40	0.20–0.40
K	1.03	0.84	0.40–1.50
Ca	0.32	0.48	0.20–0.40
Mg	0.15	0.20	0.10–0.30
S	0.13	0.22	0.20–0.30
Micronutrients (ppm)			
Cu	6	6	4–20
Zn	32	29	30–150
Mn	161	229	100–250
Fe	239	416	60–200
B	29	37	20–100

*From Landis and others *(6)*.

Conclusions

Ruter and van de Werken *(10)* question the reasons for using dolomitic limestone with container-grown plants, concluding that nursery managers should question traditional nursery practices as the first step to improve stock quality. Growers who have used their trusty growing medium for years may want to inquire whether it contains incorporated limestone. Although media with incorporated dolomite

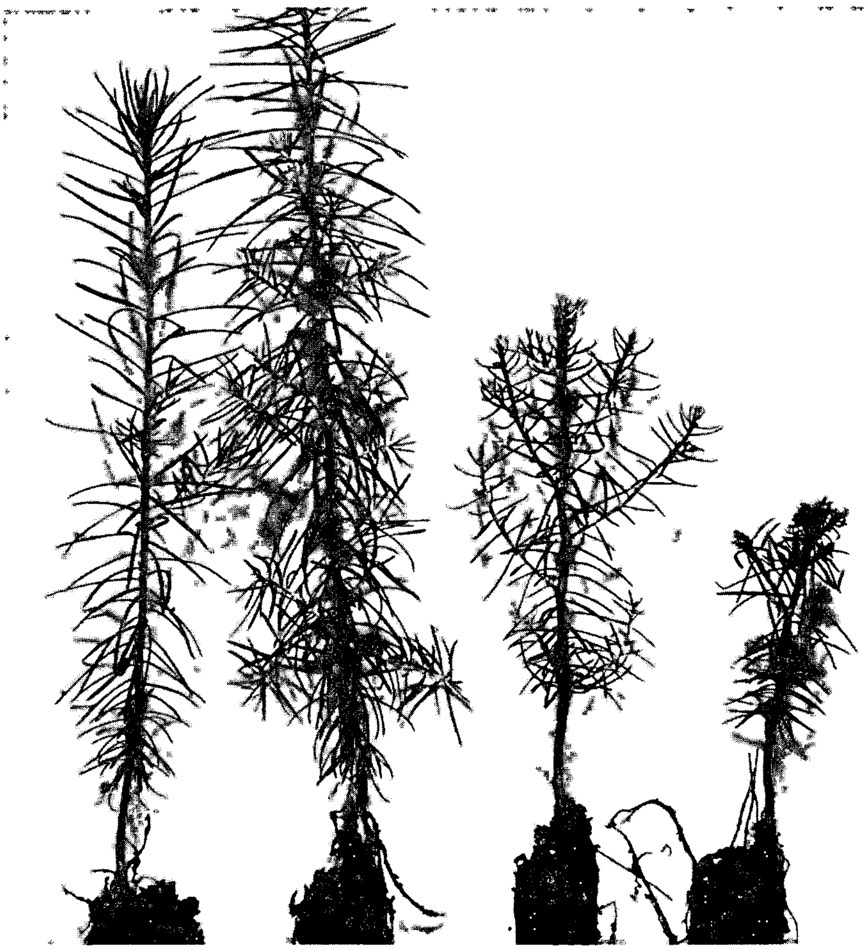

Figure 5—*Two normal Douglas-fir seedlings* (**left**) *grown in dolomite-free growing medium and two distorted seedlings* (**right**) *grown in medium with incorporated limestone.*

Table 3—*Growth of Douglas-fir seedlings in growing medium with dolomitic limestone and limestone-free growing medium*

Seedlot/ treatment	Height (cm)	Root collar diameter (mm)
DF 25-1428		
Medium with limestone	15.7*	2.86*
Medium without limestone	23.9*	2.64*
DF 25-2508		
Medium with limestone	13.1*	2.58
Medium without limestone	23.3*	2.54

*Different at the $P < 0.05$ level of significance using Tukey's LSD.

had traditionally been used for years in northern Idaho, the circumstantial evidence reported here indicates this may have caused a serious problem.

Our observations indicate that incorporated lime induced iron deficiency in Douglas-fir seedlings, although other micronutrient deficiencies may have been involved. Dangerfield *(3)* found that the formulation of the fertilizer applied during the growing season had a significant effect on the seriousness of lime-induced chlorosis. This phenomenon could explain why seedling growth was unaffected at three of the five nurseries participating in this study. Landis and others recommend no liming materials be incorporated into the growing medium for three reasons *(9)*:

1. It is difficult to obtain good distribution of limestone during mixing.
2. The pH of most peat-vermiculite growing mixes is usually adequate and routine irrigations and fertilizations will raise pH.
3. Calcium and magnesium nutrition can be adjusted more quickly and accurately using water-soluble fertilizers than by using dolomitic limestone.

The solution to the potential dolomite problem is as easy as requesting medium without limestone. In the following year, three nurseries in northern Idaho sowed part or all of their crops in dolomite-free medium with little or no adjustment to growing regimes, and their seedlings were of good to excellent quality.

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Field Trials of Root Dipping Treatments for Red Pine, Jack Pine, and White Spruce Nursery Stock in Minnesota

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*Root dipping treatments for moisture retention were tested for red pine (*Pinus resinosa *Ait.), jack pine (*P. banksiana *Lamb.), and white spruce (*Picea glauca *(Moench) Voss) in two separate field trials. Results were mixed, but they suggest that survival is not necessarily increased by using the root dipping products tried.* Tree Planters' Notes 41(3):18-20; 1990.

Bareroot seedlings are susceptible to loss and growth stunting resulting from summer drought after planting. Dipping the seedling roots in polymer root dip products before planting has the potential of reducing water loss through transpiration. A number of new superabsorbent products have been introduced recently that have improved capabilities in protecting seedling roots from moisture loss.

However, published results of survival and growth enhancement using treated seedlings are somewhat mixed. For example, Tung *et al.* *(7)* reported no increase in survival or growth of seedlings of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) during any of three growing seasons included in the test when treated with Terra-Sorb®. Similar results were reported earlier with 2+0 Douglas-fir treated with a Symbex root dip *(2)*. Ingram and Burbage *(3)* found that Terra-Sorb-treated seedlings of live oak (*Quercus virginiana* Mill.) had 13% less survival than those sprayed with water in their controlled study.

The commercial root dips do increase water-holding capacity of soils *(1)* and compare favorably with the clay slurry dips often used for seedling root protection *(6)*. They have been recommended as a precautionary measure against drought-induced mortality *(4)*, but their effectiveness will vary with weather conditions such as relative humidity during lifting *(5)*.

1987 Field Trial

In spring 1987, a field trial was conducted in northwestern Minnesota to test the effectiveness of Terra-Sorb in protecting seedling roots from drying out before and after planting. This area is subject to extensive drought during the growing-season, which can be critical to newly planted seedlings. Terra-Sorb is reported to be a "super-concentrated absorbent capable of absorbing hundreds of times its weight in plant available moisture." Its primary use is to maintain optimum soil moisture levels and provide a balance of water available to plant roots.

In this first study, seedlings root dipped into Terra-Sorb (.25 pound per 5 gallons water) and untreated trees were then exposed to various air drying periods before planting and then compared. For treated trees, these periods were: immediate planting after dipping; 5, 10, 30, and 60 minutes; control trees were planted with no air drying and after being exposed to the air for 3, 5, and 10 minutes. Three species were used—red pine, jack pine, and white spruce. Five trees were planted for each species-treatment combination. The conditions of planting were relatively dry soil (Faunce sand), air temperature of 59 °F, relative humidity of 21%, and NW wind at 5 to 10 mph. Precipitation received during 1987 was 16.5 inches or 5.0 inches below the 10-year normal.

Survival and growth of the study trees were monitored for three growing seasons (table 1). Seedling height and leader growth measurements are not included because browsing prevented valid comparisons. It should be noted that the sample size used in this trial was extremely small and treatments were not replicated. Results demonstrate interesting trends but not definitive conclusions.

The results showed increased survival of treated trees for red pine and jack pine but not white spruce after the first growing season. This is contradictory to Magnussen's results *(4)* using the polymer

Table 1—*Summarized results of 1987 plantings of red pine, jack pine, and white spruce treated with Terra-Sorb® and air dried for varying periods*

	Mean percent survival*	
Air drying (min.)	Oct. 1987	Aug. 1989
3+0 Red pine		
Control		
0	80	0
3	60	0
5	40	20
10	60	0
Terra-Sorb		
0	100	100
5	100	80
10	100	60
30	80	0
60	40	10
2+0 Jack pine		
Control		
0	100	80
3	40	40
5	60	40
10	100	100
Terra-Sorb		
0	100	80
5	100	100
10	100	100
30	100	100
60	20	20
3+0 White spruce		
Control		
0	100	0
3	100	0
5	100	20
10	100	20
Terra-Sorb		
0	80	20
5	100	0
10	100	40
30	100	0
60	80	0

*Five seedlings per species-treatment combination, unreplicated design.

Water-lock® to coat the roots of red pine and white spruce. He reported a 24% increase with treated white spruce compared to control but no significant effect on red pine. The 1987 trial also showed a substantial decrease in survival after an air drying period of 60 minutes, especially with red and jack pine. This is similar to Mullin's results *(5)* after exposing seedling roots of white pine, red pine, and white spruce for periods ranging from 0 to 3 hours. After 60 minutes of exposure, his data showed an average mortality 42% higher than that of the controls.

The third-year survival inventory indicates similar survival results for treated red pine and jack pine seedlings compared to the control. White spruce survival decreased substantially for both treated and untreated seedlings.

1989 Field Trials

Results from the 1987 field trials stimulated interest in further exploration of the use of commercial root dips in Minnesota before outplanting. A study was installed on nine areas in spring 1989 using seedlings treated with Terra-Sorb or Terra Verde Growing Polymer®, and untreated seedlings. Growing Polymer is a polyacrylamide-based product designed to protect bare tree roots from desiccation and provide available water for the root after planting. Wolcyn reported a 17% increase in survival of Scotch pine transplants when treated with this product compared to a control *(8)*.

Five replications of 25 trees each were planted using each treatment on each of the nine sites. Planting and on-site root dipping were done by regular contract planters for the Department of Natural Resources, Division of Forestry. Weather conditions at time of planting were not monitored for each site but covered the broad range from ideal to adverse. The 4-week period following planting was droughty. The study sites are described and soil types are listed in table 2 along with first-year survival results.

Statistical analysis of the data indicates that there is a significant mean survival difference ($p = 0.05$) between root dip treatments on only two of the sites. On the other seven sites, at the end of the first growing season, mean seedling survival was not increased by root dip treatment when compared to control.

The seedlings receiving root dip treatments both had significantly higher survival than controls on both the Baudette #1 and Hill City sites. There was no statistical variation between using the two root dip treatments on either site even though on the Terra Verde-treated seedlings planted on the Baudette site had an average of 18.4% higher survival than the Terra-Sorb treatment. On Baudette #2 site, there was no significant difference

Table 2—*Conditions of 1989 root dip study and mean percent survival after one growing season*

Study site and species*	Description of site	Soil type	Percent survival† Terra Sorb®	Terra Verde	Control
1. Baudette (JP)	Leno scalping, clean planting site	Hiwood loamy fine sand	64.0b	82.4a	52.8b
2. Baudette (JP)	Replant, undisturbed duff layer	Hiwood loamy fine sand	62.4b	83.2a	76.8ab
3. Deer River (RP)	Slash raked, clean planting site level	Redby loamy fine sand	76.0a	60.0a	70.4a
4. Deer River (RP)	Slash raked, clean planting site hilly	Marquette loamy sand	68.0a	80.0a	84.0a
5. Hill City (RP)	Replant, grass competition	Cushing sandy loam	71.2a	69.6a	49.6b
6. Orr (RP)	Slash raking, slash and debris, rock	Toivola loamy sand	36.0a	55.2a	44.0a
7. Orr (RP)	Slash raking, slash and debris	Loamy sand	67.2a	75.2a	65.6a
8. Warroad (JP)	Leno scalping, jack pine cut over	Faunce sand	85.3a	82.0a	88.0a
9. Warroad (JP)	Leno scalping, glyphosate application	Hiwood loamy fine sand	50.0a	53.3a	47.3a
Mean			64.4	71.2	64.3

* 5 replications per study site (6 at Warroad), 25 trees per replication. JP = jack pine, RP = red pine.
† Means within a row followed by different letters differ significantly (P = 0.05).

in mean survival between the control and either one of the root dip treatments, but Terra Verde-treated seedlings showed significantly greater survival rates than those treated with Terra-Sorb; the difference was 19.8%.

These results seem to indicate that use of commercial root dips does not necessarily increase survival of red pine and jack pine. It may well be that, as Magnussen (1986) suggests, these treatments offer a precautionary protection measure against drought. Seedlings used in this study may not have been drought-stressed to the point of the root dip treatments having any effect. Monitoring will be continued for several more growing seasons.

Our study results should not be interpreted as a final judgment of root dip treatment. The results and the cited literature show a need for a carefully designed study including replications of simulated drought-stressed seedlings. This might include lifting, handling, and shipping under conditions ranging from normal to adverse. Or, it might be designed similar to the 1987 study to include varying periods of air drying.

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Nursery Practices That Improve Hardwood Seedling Root Morphology

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*Three years of work at the State forest nurseries in Illinois, Indiana, Iowa, Missouri, and Ohio have shown that bed density control, undercutting, and seed source control can influence the root system morphology of northern red oak (*Quercus rubra *L.), white oak (*Q. alba *L.), and black walnut (*Juglans nigra *L.) seedlings. Red and white oak seedlings with five or more permanent first-order laterals (roots > 1 mm in diameter) and walnut seedlings with eight or more such laterals survive longer and compete better after field planting than seedlings with fewer lateral roots. Undercutting red oak after the second or third flush of stem growth is complete and undercutting walnut during mid- to late July results in more laterals because wound roots develop near the cut surface. Seed source also had an effect on the number of laterals produced by seedlings.* Tree Planters' Notes 41(3):21–32; 1990.

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Managers of bareroot nurseries work hard to produce the highest quality seedlings possible. They face a challenging job. No two nurseries are alike, and variations of soils and microclimates within a nursery may be as great as variations between nurseries. Variability of climate and seed crops produces situations that are not easily controlled by the nursery manager and may dramatically affect the quality of the crops.

Variability can be reduced in part by cultural practices. Forest nurseries in five of the Central States (Iowa, Illinois, Indiana, Missouri, and Ohio) have established a cooperative to improve cultural control of hardwood seedling quality. This paper will summarize 3 years of work by the cooperative and suggest standards for improving root and shoot characteristics of northern red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), and black walnut (*Juglans nigra* L.) through bed density control, undercutting, and seed-source control. Red oak and black walnut will be discussed in detail.

The commercial production of bareroot seedlings subjects them to stress not encountered by similar plants in a natural setting. Roots that are cut and extracted from their normal environment are exposed to the harshest of conditions. As a result, lateral roots less than 1 mm in diameter are usually lost. This loss produces an imbalance in the shoot to root ratio and reduces the chance for successful field establishment and competitive growth of seedlings. If sufficient large first-order lateral roots are not present, the seedlings will either not survive or not grow competitively when field planted.

First-order lateral roots greater than 1 mm in diameter (permanent laterals) are needed to provide sites for regenerating higher order roots. In recent studies *(1-8)*, researchers have suggested that there is a critical number of permanent first-order laterals needed to ensure that each species survives and grows when planted in the field. Most of the work of the cooperative has focused on increasing the number of permanent roots of oak and walnut seedlings and on field testing the responses.

Bed density and undercutting were identified as two cultural treatments that could directly increase the number of permanent roots. Both shoots and roots of seedlings respond to the space in which they grow. As bed density increases, roots seem to be more restricted than shoots. Healthy shoots can be produced from deficient root systems in the nursery because ideal conditions of moisture and nutrition are easily supplied. However, seedlings with good shoots but deficient roots respond poorly in the field.

Undercutting is the practice of drawing a blade horizontally through the soil at a given depth below the root collar, at a time other than lifting. The term *root pruning*, which has also been used to identify this practice, is better defined as the practice of clipping off excess lengths of roots after the seedling has been lifted from the nursery bed.

The rationale for undercutting can be found in nature. Naturally growing root systems are constantly being injured as they hit rocks in the soil or are damaged and consumed by soil organisms. Replacement roots are rapidly produced because the wounded area acts as a carbon sink, attracting sugars from elsewhere in the plant. As a result, three to six *wound roots* develop rapidly at or just above the wound. These same roots are produced from the lifting wound after the seedling is field planted, and act as permanent roots produced from the taproot.

Undercutting also makes sense in the nursery setting because seedlings such as oak and walnut can produce radicles growing 18 to 24 inches deep during the first growing season. These seedlings are normally lifted at 10 to 12 inches, thus cutting off a significant portion of the radicle. If these radicles were cut at a depth of 6 to 8 inches and new wound roots were produced, the lifted seedlings would have more potential sites for higher order root regeneration. Such seedlings would be more competitive in the field.

Methods

In the spring of 1987, the present state of seedling production was characterized in a preliminary study. Five-hundred randomly selected, ungraded seedlings of northern red and white oak and black walnut were examined from all but two of the cooperating nurseries (the Jasper-Pulaski and Vallonia Nurseries in Indiana). Routine cultural practices for each nursery were used to raise these 1 + 0 bed-run seedlings. Bed densities varied among the nurseries and ranged from 8 to over 20 per square foot. Samples were collected by selecting 10 to 15 seedlings from 10 randomly located positions in 400-foot-long beds. Seedlings were kept fresh, then bagged and shipped to Ames, IA, for analysis. Seedling measurements included

- height from the root collar to the base of the terminal bud.
- diameter measured at approximately 0.5 inch above the root collar.
- the number of first-order roots greater than 1 mm.

During spring 1987, studies were established to test the effect of bed density and undercutting on the production of first-order roots at each nursery (except for the Vallonia Nursery). Densities of 3, 6, and 12 seedlings per square foot for northern red and white oak and of 3, 6, and 9 per square foot for black walnut were used. These densities were established by thinning existing seedlings from the beds. Half the plots were undercut when taproots at their 6-inch depth measured 1/4 to 1/2 inch in diameter. Plots received the fertilizer, weeding, and irrigation treatments customary at their respective nurseries.

Seedlings at each nursery were lifted during spring 1988; 40 were randomly selected from each subplot (160 to 240 seedlings per treatment). The same criteria were used to measure the seedlings. In addition to the number of permanent first-order lateral roots, the number of wound roots was also counted. Wound roots were identified as roots arising at or just above the wound created by the undercutting blade.

During the 1988 growing season, various combinations of frequency and timing for undercutting were applied at different nurseries. Frequency of undercutting ranged from zero to seven. Timing ranged from as early as the second week in June to as late as the last week in August.

In addition to studies of the timing and frequency of undercutting, progeny comparisons for up to ten mother trees for each species were established at each nursery. Seedlings were grown at a density of 6 per square foot and were not undercut.

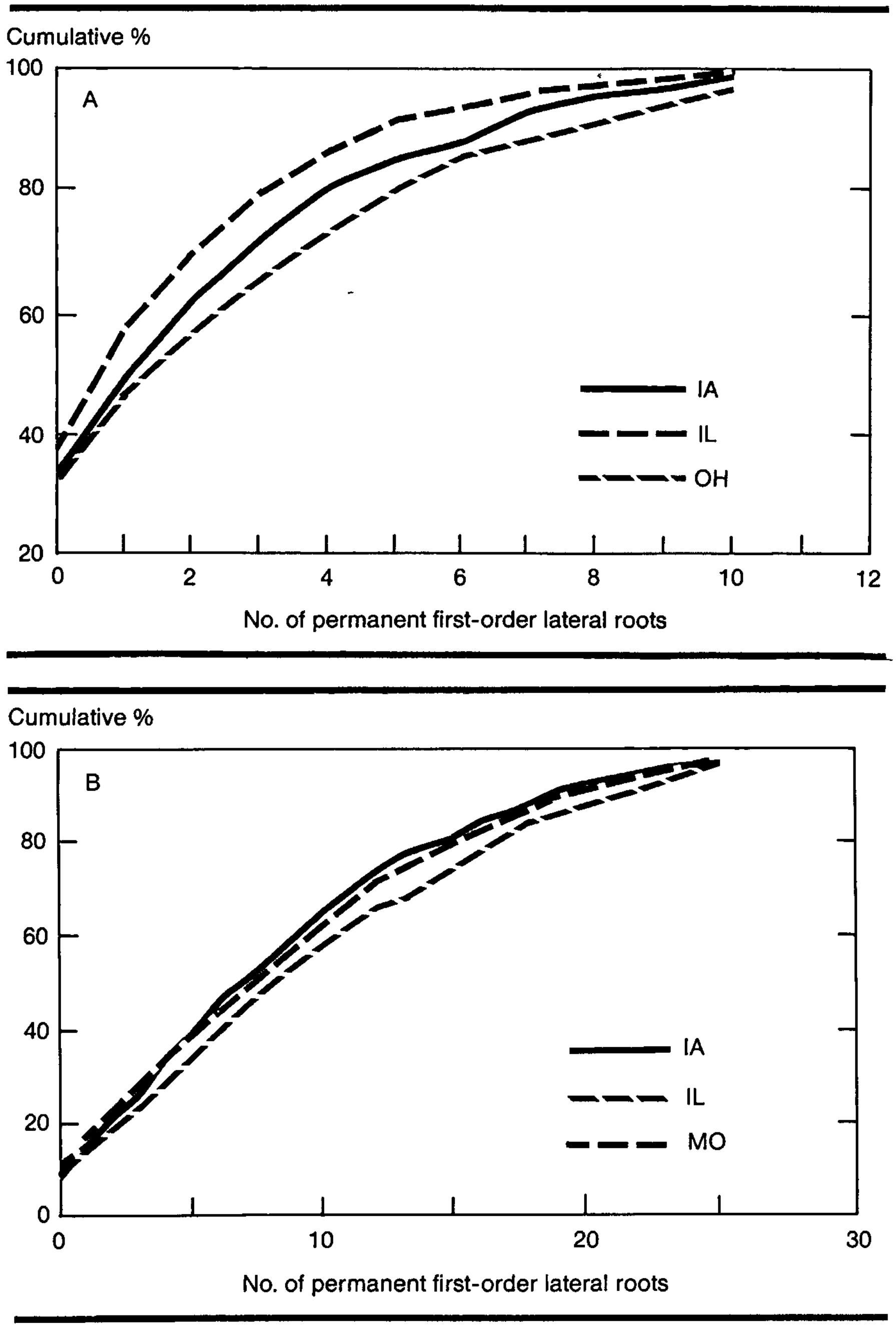


Figure 1*—Permanent first-order lateral roots of typical 1+0 northern red oak* **(A)** *and black walnut* **(B)** *planting stock, lifted in spring 1987 in nurseries in Iowa (IA), Illinois (IL), and Ohio (OH).*

Seedlings treated during the 1988 growing season were lifted in the spring of 1989, and samples from both studies were field planted at their respective local nurseries or at a site near Newton, IA.

Results and Discussion

The results presented have been selected from across the five participating states. Most of these preliminary responses are duplicated in the other states. Those selected for inclusion show some of the clearest trends.

Bed-run responses. Permanent first-order lateral roots were counted on bed-run seedlings sampled during the spring of 1987 (fig. 1A and 1B). These seedlings were grown at accepted nursery bed densities and thus provide a picture of typical planting stock before the implementation of density and undercutting studies. Depending on the nursery, we found that 56 to 70% of the red oak seedlings had less than two permanent first-order lateral roots and that only 8 to 20% of the red oak seedlings had five or more permanent first-order lateral roots (fig. 1A). Data for white oak seedlings at the Missouri and Ohio nurseries (not included in the graphs) indicated that 32 to 34% of the seedlings, depending on the nursery, had fewer than three permanent first-order laterals and that 37 to 42% had five or more.

We also found that 12 to 16% of the walnut seedlings, depending on the nursery, had less than two permanent first-order lateral roots and that 67 to 72% had five or more (fig. 1B). Forty-eight to 56% of walnut seedlings had eight or more permanent, first-order laterals.

The range in percentages shows the variations among nurseries before the use of undercutting or specific density controls. Because of inherent nursery differences such as site, climate, seed source, and cultural practices, one would not expect to have the same percentages. However, the distribution

Table 1—*Responses of red oak seedlings to bed density and undercutting*

Density/ undercutting	Height (in)	Diameter (in)	No. of permanent roots > 1 mm		
			1st-order	Wound	Total
Illinois					
3/ft²					
Yes	15.3	0.32	13.4	6.1	19.5
No	20.9	0.39	10.8	—	10.8
6/ft²					
Yes	14.9	0.29	10.6	5.8	16.4
No	19.1	0.33	8.8	—	8.8
12/ft²					
Yes	15.2	0.27	8.7	6.2	14.9
No	18.1	0.30	6.6	—	6.6
	D,U,DU	D,U,DU	D,U		
Indiana					
3/ft²					
Yes	16.2	0.27	11.8	4.0	
No	18.8	0.31	14.8	—	
6/ft²					
Yes	16.1	0.25	11.5	4.8	
No	17.3	0.26	12.4	—	
12/ft²					
Yes	15.3	0.24	8.0	4.9	
No	17.2	0.25	9.5	—	
	D,U	D,U,DU	D,U	D	
Ohio					
3/ft²					
Yes	16.2	0.30	14.3	2.2	
No	17.8	0.30	12.0	—	
6/ft²					
Yes	15.5	0.26	9.8	1.8	
No	15.9	0.27	8.4	—	
12/ft²					
Yes	13.2	0.23	7.2	1.3	
No	15.0	0.25	7.1	—	
	D,U	D,U	D,U,DU	D	

Wound roots are roots > 1 mm developing around the undercutting wound. Significant (α = 0.01) effects of density (D), undercutting (U), and density by undercutting interaction (DU) were noted for the indicated characteristics.

of the number of roots among nurseries is fairly consistent, especially for walnut.

Preliminary data suggest that five or more permanent first-order laterals are needed for red and white oak, and eight or more for walnut seedlings to establish successfully in the field (unpublished data). The large number of seedlings having insufficient numbers of these critical roots suggests that introducing a large cull factor, based on root system quality, into grading systems would assure high-quality planting stock. On many seedlings, however, cultural practices could be modified to reduce the cull percentage by increasing the number of permanent first-order laterals.

Response to density and undercutting. In spring 1987, we began a study to determine the effects of density and undercutting on the number of first-order lateral roots, and the initial height and diameter of seedlings (tables 1 and 2). For red oak and walnut, there was a decrease in height growth as bed density increased and as undercutting was done. These results are expected: increased root density increases competition for space, whereas undercutting changes the source-sink response for carbohydrates in favor of the roots. Undercutting has long been used to control the height of conifer seedlings.

For both red oak and walnut, undercut seedlings had greater numbers of total first-order permanent lateral roots than their uncut counterparts did (tables 1 and 2). The increased number of roots resulted from the addition of 2 to 6 wound roots and from the increased diameter of lateral roots already present above the wound. White oak showed similar results.

The number of wound roots produced is related to the timing of undercutting and to ambient conditions at the time of undercutting, such as temperature and moisture. Recent studies have focused on identifying these effects, and their initial results indicate that wound roots, as well as original laterals, persist and grow in the field (unpublished data).

The Iowa data are not presented here because of a practical problem with undercutting. Iowa seedlings were lifted above the depth of undercutting at harvest so that no new roots were recovered and the response could not be measured. If undercutting is intended to increase first-order roots on seedlings, the cut must be made well above the eventual lifting depth.

As bed density increased, fewer permanent first-order lateral roots were produced in both undercut and uncut treatments at all nurseries. At the Illinois nursery, density did not affect the number of

Table 2—*Responses of walnut seedlings to bed density and undercutting*

Density/ undercutting	Height (in)	Diameter (in)	No. of permanent roots > 1 mm		
			1st-order	Wound	Total
Illinois					
3/ft²					
Yes	22.9	0.40	14.4	4.0	18.4
No	35.0	0.46	10.7	—	10.7
6/ft²					
Yes	23.9	0.36	10.6	3.5	14.1
No	30.9	0.40	7.5	—	7.5
9/ft²					
Yes	23.3	0.36	8.6	3.2	11.8
No	30.3	0.39	6.6	—	6.6
	D,U,DU	D,U	D,U	D	
Missouri					
3/ft²					
Yes	14.6	0.30	11.7	4.6	16.3
No	17.0	0.32	13.7	—	13.7
6/ft²					
Yes	15.9	0.28	8.8	4.1	12.9
No	18.3	0.30	9.8	—	9.8
9/ft²					
Yes	17.9	0.26	6.4	3.3	9.7
No	19.6	0.27	8.2	—	8.2
	D,U,DU	D,U	D,U,DU	D	

Wound roots are > 1 mm developing around the undercutting wound. Significant (α = 0.01) effects of density (D), undercutting (U), and density by undercutting interaction (DU) were noted for the indicated characteristics.

wound roots produced by the undercutting treatment. At all other states, however, the number of wound roots produced decreased as density increased. These data show the strong effect that density control plays on the development of seedling root systems. To produce adequate root systems, the three hardwoods studied here should be grown at densities of no greater than 6 seedlings per square foot.

Figures 2 and 3 show the cumulative distribution of red oak and walnut seedlings (%) by numbers of first-order lateral roots, for two representative states. White oak showed a response similar to the response of both red oak and walnut. In all cases the undercutting treatment produced—at a given density—more seedlings with greater numbers of total first-order lateral roots (first-order laterals plus wound roots) than the no cutting treatment did. The undercutting treatment on 3 seedlings per square foot density produced the largest number of seedlings with large numbers of roots. The effect of both density and undercutting on lateral root production is clearly shown in these figures. Although the graphs are not identical, they are quite similar in actual values and in curve shape. Reducing bed densities and undercutting red and white oak and black walnut seedlings in the Central States will produce more seedlings with increased potential for both survival and good early growth in field.

Height and diameter correlations with numbers of roots. Although walnut shows very little height change with varying root numbers (fig. 4A), red oak shows a rapid increase in height as the

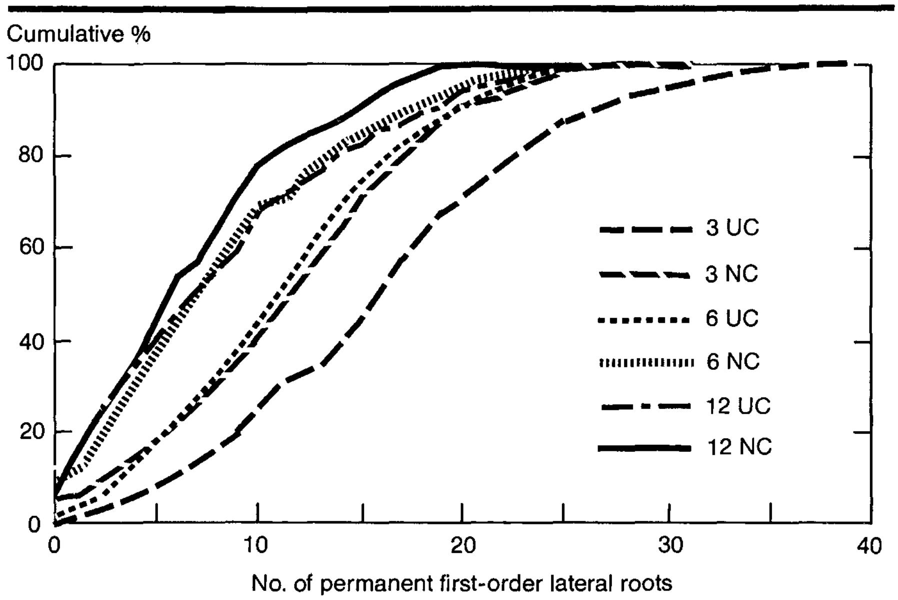


Figure 2—*Cumulative percentage of undercut (UC) and not cut (NC) 1+0 northern red oak seedlings lifted from Ohio nurseries in 1988, grown at densities of 3, 6, and 12 seedlings per square foot, with first-order laterals.*

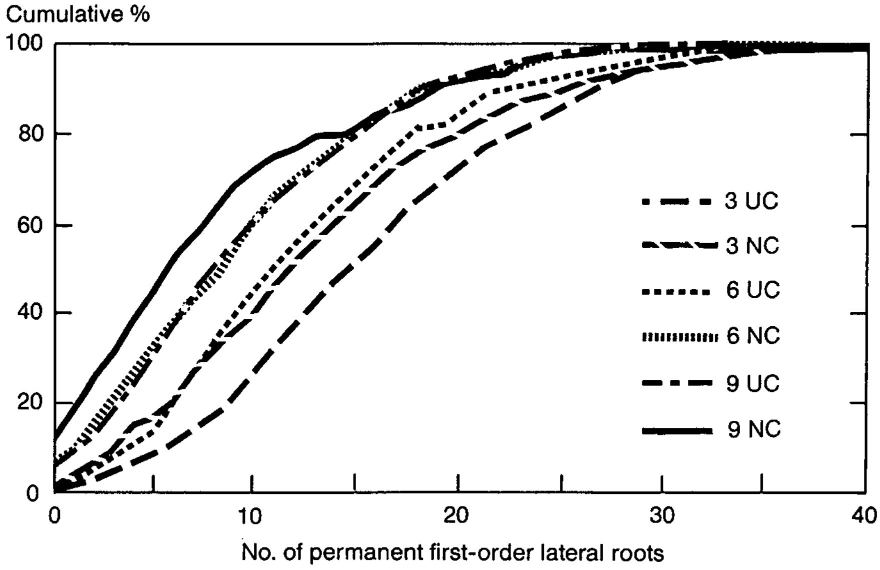


Figure 3—*Cumulative percentage of undercut (UC) and not cut (NC) 1+0 black walnut seedlings lifted from Missouri nurseries in 1988, grown at densities of 3, 6, and 9 seedlings per square foot, with first-order laterals.*

number of laterals increases from five to eight (fig. 5A). If root morphology is indeed important in the successful establishment of seedlings, grading walnut seedlings by height alone will not reflect their potential for success.

Seedling diameter also decreased as bed density increased and as undercutting proceeded. The differences in diameter between undercut seedlings and non-undercut seedlings were usually less than 0.2 inches. Figures 4B and 5B suggest that, especially among seedlings with lower numbers of roots, diameter may be a good predictor of root morphology. The ease of grading by stem diameter or by root number may differ, however.

Traditionally, seedlings have been graded by diameter, but it is doubtful whether most graders can estimate diameter well. It would probably be easier to inspect a seedling's root system to distinguish whether it has five to six or more permanent first-order roots than to determine whether it has a .25-inch stem diameter.

Responses to date and frequency of undercutting. In walnut seedlings in the Illinois nursery (fig. 6A-C) and in other states, the total number of first-order roots increased with later dates of undercutting and with more frequent undercutting. The increase resulted from both increased numbers of wound roots and increased diameters of laterals already present.

Illinois walnut seedlings undercut during the month of June and the first week in July showed greater height growth than uncut seedlings. Seedlings undercut on June 8 were probably too large for most field planting situations; those undercut on July 21 were smaller than the uncut seedlings but were still taller than 18 inches.

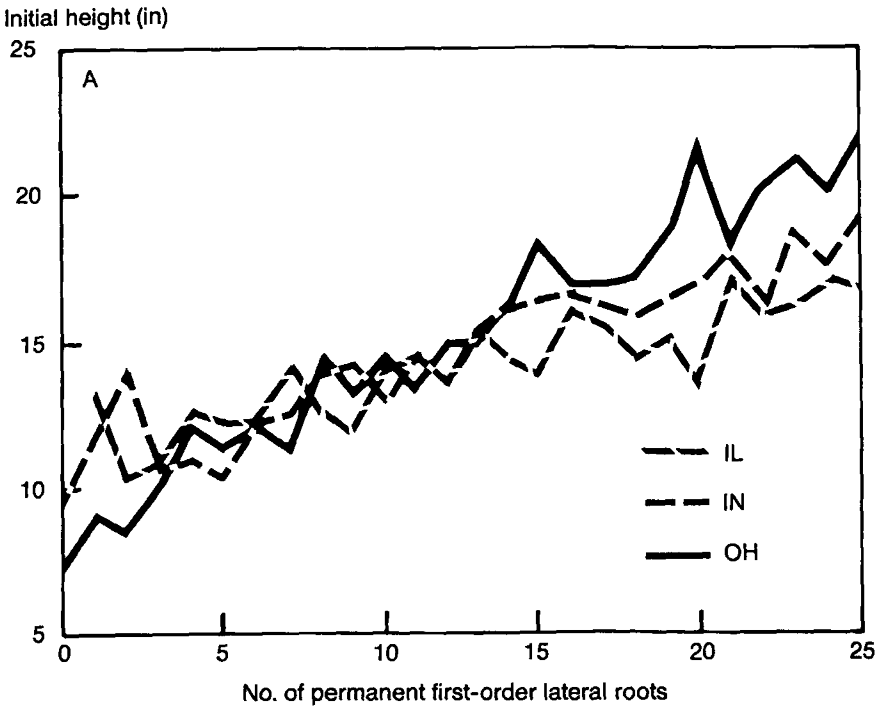
Diameters of seedlings showed few differences in response to undercutting. Seedlings undercut in late July had the smallest diameters, but the remaining seedlings exhibited few differences. Diameters in most cases were about 5/16 inch, a good size for walnuts.

Based on this information, it would seem best to undercut walnut once in late June or in early July. It is not necessary to use multiple undercuts unless there is a height growth problem. This recommendation is based on data from only 1 year and could change depending on the weather. There have been years when multiple undercutting was necessary to reduce dramatic height growth.

The number of permanent roots in Illinois red oak seedlings increased with later dates of undercutting, until late July (fig. 7A-C). However, even the late July undercutting produced more permanent lateral roots than were produced on the seedlings that had not been undercut.

Seedling height decreased with undercutting, especially for the two June dates. The late July date, which produced the fewest permanent lateral roots, produced the tallest undercut seedlings. This would suggest that undercutting redirects carbohydrate movement from shoot to root growth. The later the undercutting, the more the carbohydrate is directed to shoot growth before it is redirected.

Seedling diameter response was almost the opposite of height response. Diameters continually decreased with later undercutting dates, possibly because diameter growth is a late-season phenomenon. Early undercutting slowed shoot growth by redirecting carbohydrates to the roots, but did not



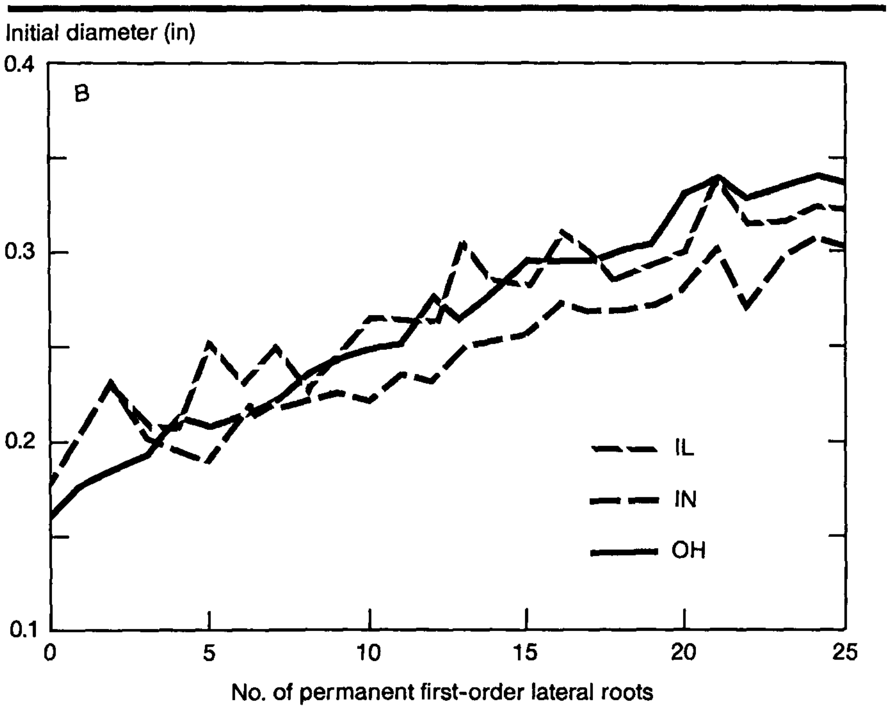


Figure 4—*Relation of initial height (A) and diameter (B) to total number of first-order laterals on 1+0 northern red oak seedlings grown in nurseries in Illinois (IL), Indiana (IN), and Ohio (OH) lifted in spring 1988. Values are means for the three densities.*

affect the diameter of these seedlings because wound roots had already been formed before major cambial growth activity began. With later undercutting, production of wound roots "robbed" the cambium of carbohydrates.

According to observations made during summer 1988, the ideal time to undercut red oak seedlings in the Central States is early to mid-July, after the second shoot flush has stopped. More specifically, seedlings should be undercut when the terminal bud has stopped expanding and the uppermost leaves have expanded to about three-quarters of their size. Another approach might be to undercut after the largest shoot flush has been completed.

In other words, undercutting should be done when the average shoot has almost reached the target height for saleable seedlings. From our observations it seems that only 3 to 4 weeks are needed for wound roots to be initiated and another 3 weeks are needed for those roots to suberize and become permanent.

The depth of undercutting is critical if the newly produced roots are to be lifted with the seedlings. Undercutting must be performed well above the lifting depth. In a nursery bed it is difficult to control undercutting depth precisely because of uneven bed heights and soil densities, but it should be possible to control depths to within 2 inches above or below the target

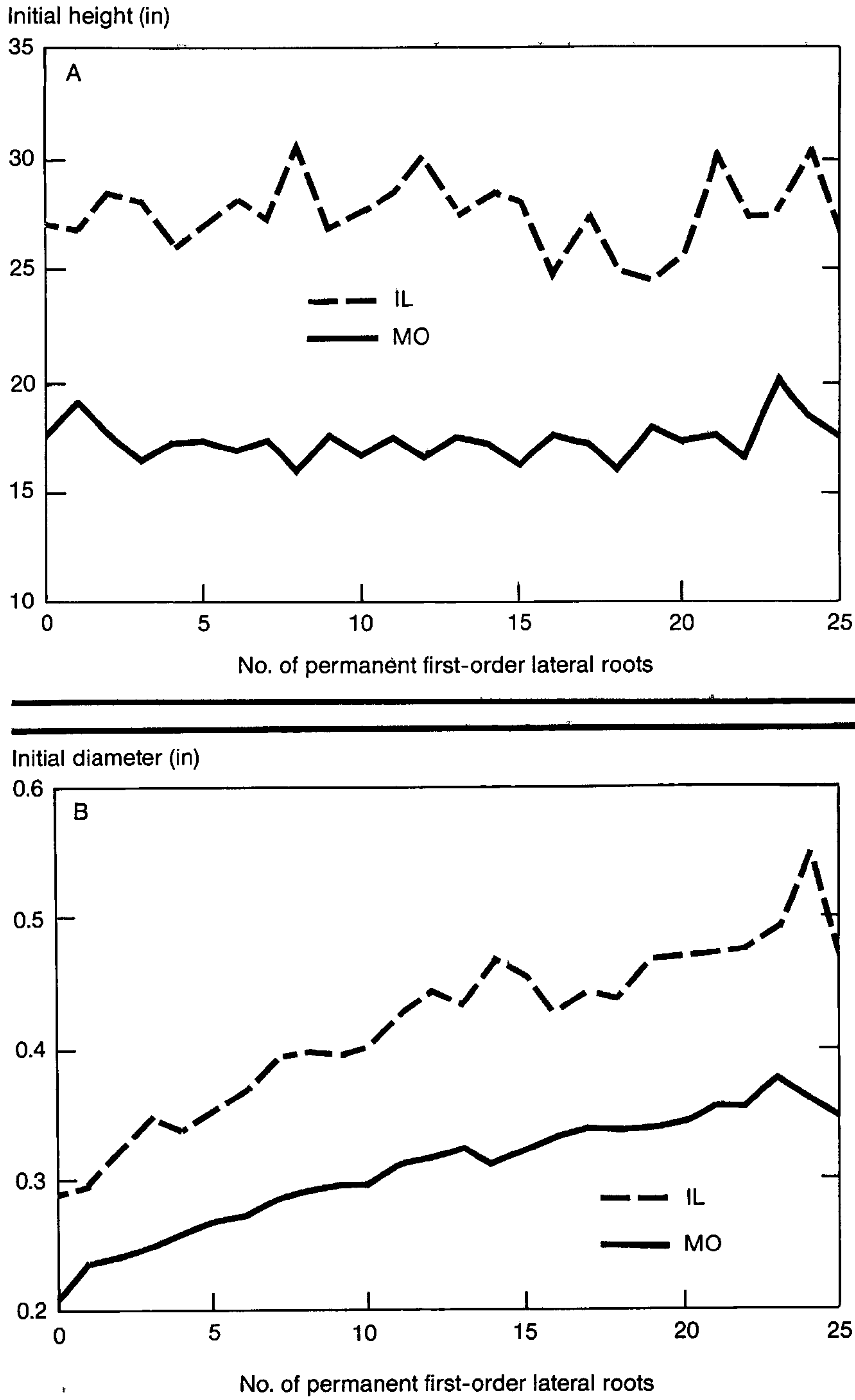


Figure 5—*Relation of initial height (***A***) and diameter (***B***) to total number of first-order laterals on 1+0 black walnut seedlings grown in nurseries in Illinois (IL) and Missouri (MO) at three densities and lifted in spring 1988.*

depth. Lifting depths are usually not deeper than 10 to 12 inches. Therefore, undercutting should be done at a depth of 6 to 8 inches. If lifting is done at shallower depths, then undercutting should also be shallower.

The ideal weather for undercutting is cool and moist, unlikely conditions for late June to mid-July. Thus, it is important for seedlings to be well irrigated no more than a day before undercutting. Seedlings should be undercut in the morning (6 to 10 am) or in the evening (after 7 pm). Seedlings should be irrigated again immediately after undercutting. It is unwise to undercut at temperatures exceeding 90 °F.

Casual observation suggests that seedlings that die as a result of undercutting are those having few lateral roots to begin with. In Iowa, in the summer of 1989, virtually all red oak seedlings that died after several beds were undercut pulled easily out of the ground because they had no roots. This suggests that under stress, undercutting seedlings could actually cull seedlings with poor root systems in the nursery bed. Research needs to be done to verify this phenomenon.

Mother-tree progeny tests. There was much variation among seed sources in terms of root numbers produced and associated height and diameters in red oak grown in Missouri (fig. 8) and walnut in Iowa (fig. 9). At this point,

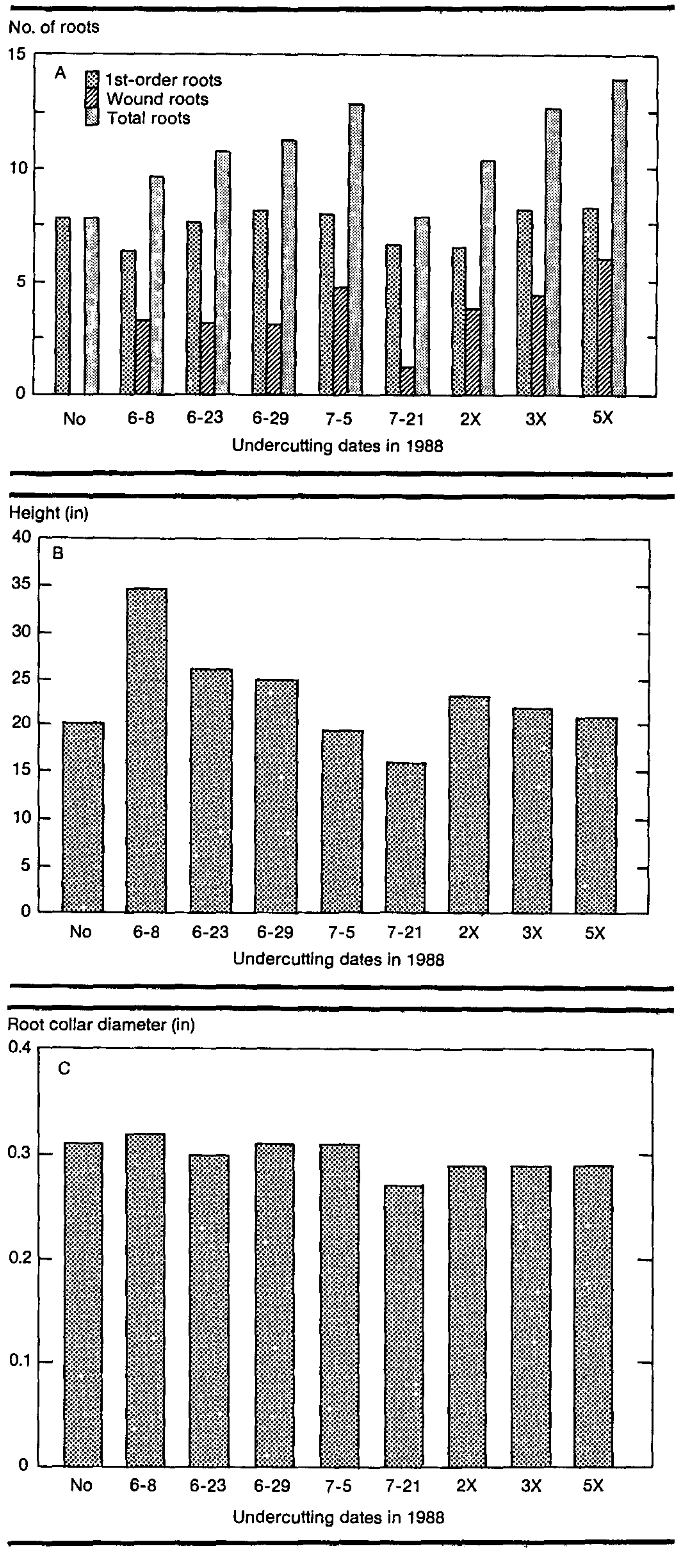


Figure 6—*Number of roots* **(A)**, *height* **(B)**, *and root collar diameter* **(C)** *of 1+0 black walnut seedlings grown in Illinois nurseries and undercut on different dates in 1988.*

we believe more attention should be paid to the morphological characteristics of seedlings from specific mother trees. Future seed orchards should include only those trees producing a high number of seedlings with a minimum number of permanent first-order lateral roots.

Summary

In certain studies (Schultz and Thompson unpublished data) of the outplanting of numerous seedlings and in recent work by Kormanik and others *(1-3, 5)*, field survival and early growth of seedlings is strongly correlated with the number of permanent first-order lateral roots that a seedling develops in the nursery.

Information from our study suggests that a competitive northern red oak seedling must have a large root system with at least five permanent first-order lateral roots > 1 mm in diameter. White oak seedlings should have root systems similar to those recommended for red oak, and walnut seedlings should have eight or more large laterals. According to our study, after 2 years in the field, seedlings with those minimum numbers of roots had greater stem diameter and significantly larger leaf area (as inferred from the numbers of leaves) than seedlings with fewer roots.

The large number of bed-run seedlings produced that did not meet these minimum criteria suggests that root morphology should

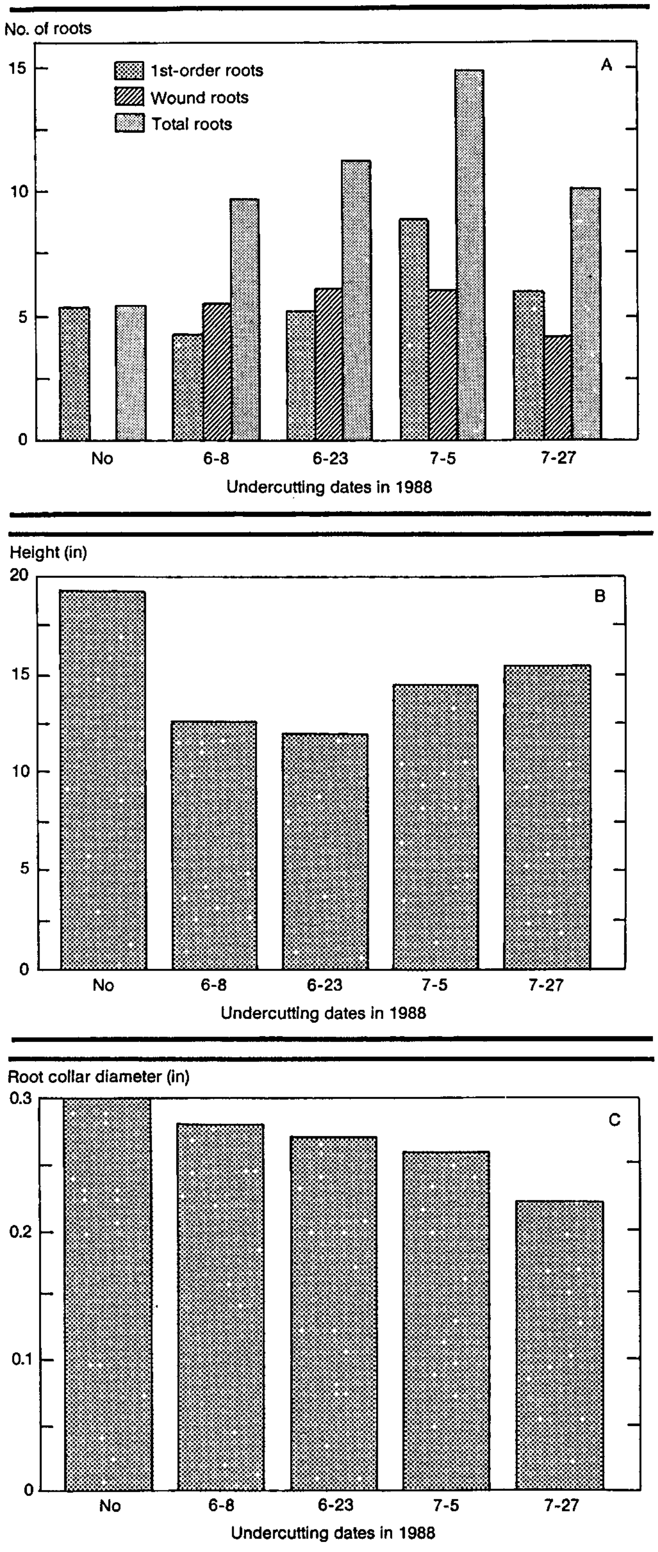


Figure 7—*Number of roots* (**A**)*, height* (**B**)*, and root collar diameter* (**C**) *of 1+0 northern red oak seedlings grown in Illinois nurseries and undercut on different dates in 1988.*

be a part of the grading scheme for bareroot seedlings. Nursery control of seedbed density and the use of timely undercutting can improve root morphology. However, there is a strong genetic component to root system expression that will require grading to eliminate root system culls *(3)*. Simply using height and/or diameter as grading criteria may not adequately identify potential for outplanting success. Recognition of the importance of root system morphology as a grading criterion will improve not only field survival but also early growth of seedlings.

According to the research work done in the cooperative, the ideal oak seedling is 14 to 16 inches tall, has a diameter of 1/4 inch, and has more than five to six permanent first-order lateral roots. The ideal walnut is 15 to 20 inches tall, has a diameter of 5/16 inch, and has 8 to 10 permanent first-order lateral roots.

Such large hardwood seedlings will require new approaches to planting. To improve hardwood seedling establishment and survival, larger equipment will be necessary to produce larger planting holes. The typical pine planting machine is inadequate for planting large hardwood seedlings, harming many larger root systems when they are forced through the machine. Larger planting machines are on the market and should be used.

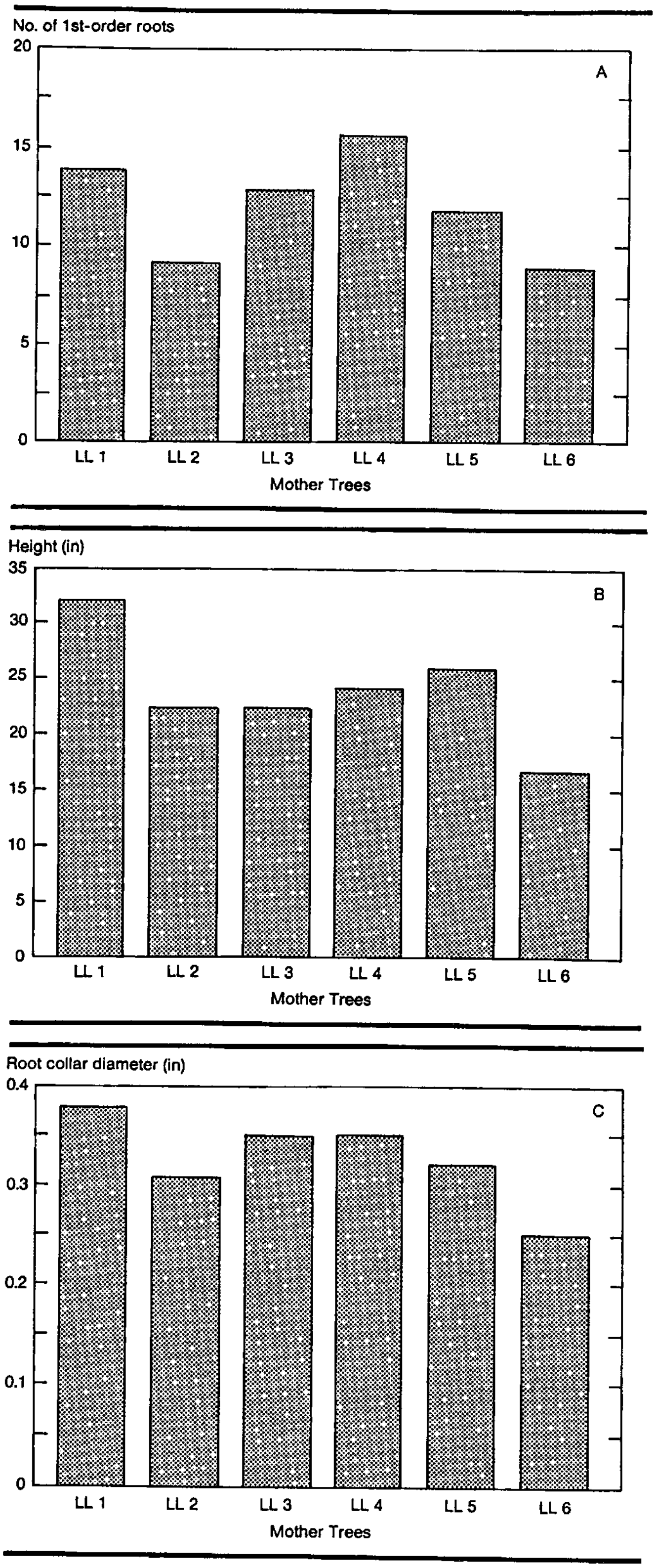


Figure 8—*Number of roots* **(A)**, *height* **(B)**, *and root collar diameter* **(C)** *of 1 + 0 northern red oak seedlings from different mother trees grown in Missouri nurseries in 1988.*

Hand planting with dibble bars is also impractical because the hole produced is not large enough. A shovel or large hodag may be necessary for hand planting. Portable two-person power augers are another option, for an 8-inch auger bit produces an adequate hole. Most of the seedlings planted for the cooperative studies were planted with such an auger. To date, there is no root morphological evidence that the auger hole constricts seedling roots if they are pruned to about 4 inches in length.

If establishing high-quality hardwood plantations is to be successful, large seedlings with well-developed permanent first-order root systems are necessary and must be planted with the proper equipment.

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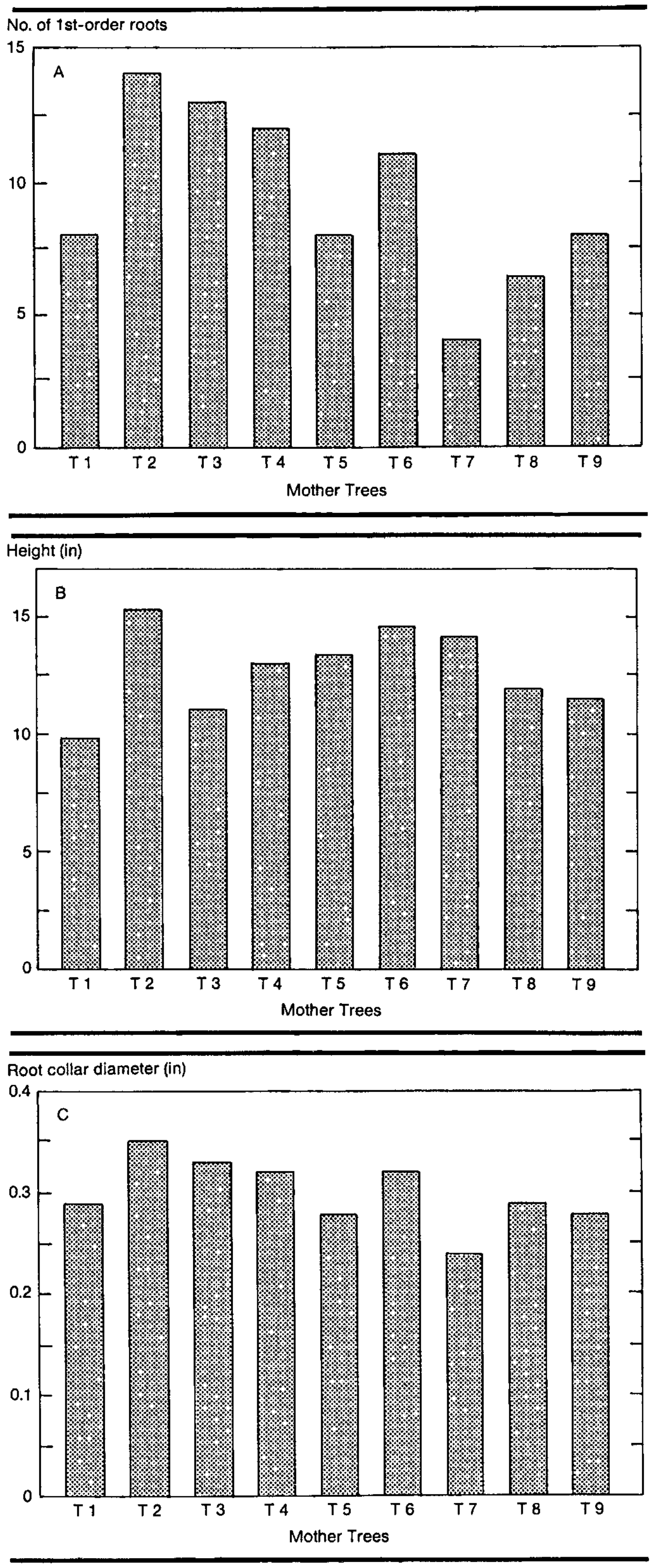

Figure 9—*Number of roots* **(A)***, height* **(B)***, and root collar diameter* **(C)** *of 1+0 black walnut oak seedlings from different mother trees grown in Iowa nurseries in 1988.*

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Water-Soluble Extracts from Leaves of Shining Sumac Inhibit Germination and Radicle Growth of Loblolly Pine

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*Water-soluble extracts from leaves of shining sumac (*Rhus copallina *L.) had a phytotoxic effect on both germination and radicle growth of loblolly pine (*Pinus taeda *L.) seeds in laboratory tests. This finding suggests that shining sumac may interfere with the regeneration of loblolly pine stands from seed.* Tree Planters' Notes 41(3):33–34; 1990.

Shining sumac (*Rhus copallina* L.) is a common shrub in southern pine forests. It is usually found growing in colonies and averages less than 3 feet in height *(2)*. Often associated with broomsedge (*Andropogon* spp.) and blackberry (*Rubus* spp.) along the edge of forest clearings, shining sumac may persist in the understory until crown closure *(1)*.

Allelopathic properties of shining sumac have been found to significantly inhibit germination and seedling growth in climax prairie ecosystems *(3)*. The known effect of shining sumac on other plants led to the present examination of the effects of water-soluble extracts from shining sumac leaves on germination and radicle growth of loblolly pine (*Pinus taeda* L.).

Methods

Shining sumac leaves were harvested on the Catahoula Ranger District of the Kisatchie National Forest at the time of leaf fall in October 1988, freeze-dried, and ground in a Wiley mill using a 2-mm screen. Seven extract solutions were made by placing 0.00, 0.95, 1.90, 3.75, 7.50, 15.0, and 30.0 g of dried leaves (equivalent to 0.0, 18.9, 37.9, 75.8, 151.5, 303.0, and 606.0 g of dried leaves per m^2 of soil surface, respectively) and 200 ml of distilled water in Erlenmeyer flasks, shaking continuously for 2 days, and then filtering under a vacuum. Distilled water was used to bring the extracts to a total volume of 200 ml each.

Germination test. Large germination trays (495.6 cm^2) were filled with medium (50% potting mixture and 50% sand) to a depth of 5 cm. Fifty stratified loblolly seeds were placed in each of seven germination trays. Each tray was then sprayed once with one of the seven extract solutions. The trays were fitted with lids so they would not have to be watered again and were placed in a germination room under standard conditions for 28 days. There were three replications of this test.

Radicle test. Stratified loblolly seeds from a common seed source (Rapides Parish, Louisiana) were germinated and held in untreated media until radicles were long enough to transplant (5 to 20 mm). Then 750 germinated seeds were randomly selected, and the lengths of their radicles measured. Seeds were divided into samples of 50 germinants, and each sample was planted in a large germination tray (495.6 cm^2) that had been filled with medium to a depth of 5 cm.

Each of the 15 trays was sprayed once at the time of planting to provide 3 treatment replications of each of the following 5 extract solutions: 0.00 (control), 0.95, 1.90, 3.75, and 7.50 g per 200 ml. The trays were fitted with lids and placed in the germination room under standard conditions. Radicle length was measured to the nearest millimeter after 3 days. The test was discontinued at this time because some radicles were reaching the bottom of the trays, and further growth would have made extracting the intact radicle difficult.

Analysis of data. Data for germination and radicle growth were recorded for each concentration of sumac extract, and differences were determined by analysis of

Table 1—*Effect of shining sumac extraction on germination of loblolly pine seed after 28 days*

Concentrations of sumac extract		% Germination	
g/200 ml	g/m²	Normal	Abnormal
0.00	0.0	93 a	0 c
0.95	18.9	95 a	0 c
1.90	37.9	95 a	0 c
3.75	75.8	92 a	0 c
7.50	151.5	86 a	6 c
15.0	303.0	52 b	43 b
30.0	606.0	29 b	69 a

Values in a column followed by the same letter are not significantly different at P = 0.05, based on Duncan's multiple range tests. Abnormality was exhibited by the radicle being dark colored and unable to penetrate the medium.

Table 2—*Influence of shining sumac extract on mean radicle growth of loblolly pine*

Concentration of sumac extract		
g/200 ml	g/m²	Radicle growth (mm)
0.00	0.00	20.0 a
0.95	18.8	18.0 a
1.90	38.0	13.1 b
3.75	75.8	3.6 c
7.50	151.5	2.1 c

Values in the results column followed by the same letter are not significantly different at P = 0.05, based on Duncan's multiple range tests.

variance (P = 0.05). When statistically significant differences were found, mean separation was determined with Duncan's multiple range tests (P = 0.05).

Results

Germination test. The concentration of shining sumac extract applied to the trays did not significantly affect total germination of loblolly seeds, but it did significantly reduce normal seedling germination (table 1).

Toxicity to radicles was seen at the higher concentrations; affected radicles were dark colored and could not penetrate the medium. With the 7.50 g/200 ml extract, few (6%) of the radicles were affected, but toxicity was significant with the 15.0 g/200 ml and the 30 g/200 ml extracts (table 1).

Radicle test. Radicle growth was normal with the 0.00 and 0.95 g/200 ml extracts (table 2). However, with the 1.90 g/200 ml extract, radicle growth was 35% less than that of the control and some radicles were black and wilted. At the 7.50 g/200 ml extract, radicle growth was only 11% of that of the control, and all radicles were black and wilted.

Discussion

In the laboratory, water-soluble extracts from leaves of shining sumac had an adverse effect on loblolly seed germination and radicle development. This phytotoxic reaction suggests that shining sumac colonies growing on forest lands may have a more adverse influence on loblolly pine establishment from natural or artificial seeding than can be explained by competition only.

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