Nursery Cultural Practices That Improve Hardwood Seedling Root Morphology

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Abstract

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 red and white oak and of black walnut seedlings. Red and white oak seedlings with five or more and walnut seedlings with eight or more permanent first-order laterals (roots > 1mm in diameter) survive longer and compete better after field planting than seedlings with fewer roots do. Bed densities of 3-6 seedlings/ft^2 increase the number of first-order lateral roots. Undercutting red oak after the second or third flush of stem growth and undercutting walnut during mid- to late July result in more laterals because wound roots develop near the cut surface. Seed source has also been shown to have an effect on the number of laterals produced by seedlings.

Introduction

Managers of bare-root nurseries work hard to produce the highest quality seedlings possible. They are faced with a very challenging job. No two nurseries are alike, and within-nursery variations of soils and microclimates may be as great as between-nursery variations. Variability of climate and seed crops produces situations, not easily controlled by the nursery manager, that may dramatically affect the quality of the crops. Variability can be reduced, in part by cultural practices. Forest nurseries in five central states (IA, IL, IN, MO, and OH) have established a cooperative to improve cultural control of hardwood seedling quality. This paper will summarize three years of work by the cooperative and suggest standards for improving root and shoot characteristics of red oak *(Quercus rubra)* , white oak *(Quercus alba),* and black walnut *(Juglans nigra)* through bed density control, undercutting, and seed-source control. White oak will not be discussed in detail.

The commercial production of bare-root seedlings subjects them to stresses not encountered by similar plants in a natural setting. Roots which are cut and extracted from their normal environment, are exposed to the harshest of conditions. As a result, lateral roots less than one millimeter in diameter are usually lost. This loss produces an imbalance in shoot/root ratios 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 not survive, or if they survive, will not grow competitively when field planted.

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First-order laterals greater than one millimeter in diameter (permanent laterals) are needed to provide sites for regenerating higher-order roots. Recent work (Kormanik and Ruehle 1987, Kormanik 1986, Kormanik and Muse 1986, Perry 1982, Ruehle and Kormanik 1986, Schultz and Thompson 1987, 1989, Schultz 1988) suggests that there is a critical number of permanent first-order laterals needed to ensure each species not only of survival, but of seedling growth 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. Good-looking shoots can be produced from deficient root systems in the nursery because "ideal" conditions of moisture and nutrition are easily supplied. Seedlings with good shoots but deficient roots respond poorly in the field however.

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 has also been used to identify this practice. But root pruning 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 subjected to predation by soil organisms. Replacement roots are rapidly produced because the wounded area is a carbon sink attracting sugars from elsewhere in the plant. Consequently, 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 18-24 inches deep during the first growing season. These seedlings are normally lifted at 10-12 inches, thus cutting off a significant portion of the radicle. If these radicles were cut at six to eight 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, a preliminary study was done to characterize the present state of seedling production. Five-hundred randomly selected, ungraded seedlings of red and white oak and of black walnut were examined from each cooperating nursery, except for the Jasper-Pulaski and Vallonia Nurseries in Indiana. The 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 ft^2. Samples were collected by selecting 10-15 seedlings from 10 randomly located positions in 400 ft-long beds. Seedlings were kept fresh, bagged, and shipped to Ames, Iowa 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, and number of first-order roots greater than 1 mm.

During the Spring of 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 $3/ft^2$, $6/ft^2$, and $12/ft^2$ for red and white oak; and of $3/ft^2$, $6/ft^2$, and $9/ft^2$ for black walnut were used. These densities were established by thinning existing seedlings from the beds. Half the plots were undercut when taproots six inches deep were between 1/4 - 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 the Spring of 1988, and 40 were randomly selected from each subplot (160-240 seedlings per treatment). The same criteria mentioned previously 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 undercutting frequency and timing were applied at different nurseries. Undercutting frequencies 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 $6/ft^2$ and were not undercut.

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, Iowa.

Results and Discussion

The distribution of permanent, first-order lateral roots of seedlings sampled during the spring of 1987 **is** presented in Figures 1A and 1B. These seedlings represented bed-run plants grown at accepted nursery bed densities. They provide a picture of typical planting stock before the implementation of density and undercutting studies. Figure 1A shows that, depending on the nursery, 56-70% of the red oak seedlings had less than two permanent first-order lateral roots. It also shows that only 8-20% of the red oak seedlings had five or more permanent first-order lateral roots. Data for white oak seedlings at the Missouri and Ohio nurseries (not included in the graphs) indicated that 32-34% of the seedlings, depending on the nursery, had fewer than three permanent first-order laterals and that 37-42% had five or more.

Figure 1B shows that 12-16% of the walnut seedlings, depending on the nursery, had less than two permanent first-order lateral roots and that 67-72% had five or more. Forty-eight to 56 percent 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 of 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, but the distribution 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 become successfully established in the field (unpublished data). The large number of seedlings having insufficient numbers of these critical roots suggests that a large cull factor, based on root system quality, should be introduced into grading systems to assure high-quality planting stock. On many seedlings, however, modification of cultural practices could be used to reduce the cull percentage by increasing the number of permanent first-order laterals.

In the spring of 1987, a density and undercutting study was established to increase the number of first-order lateral roots. Tables 1 and 2 present the effects of density and undercutting on the initial height and diameter of seedlings. For red oak and walnut, there was a decrease in height growth as bed density increased and as undercutting proceeded. 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.

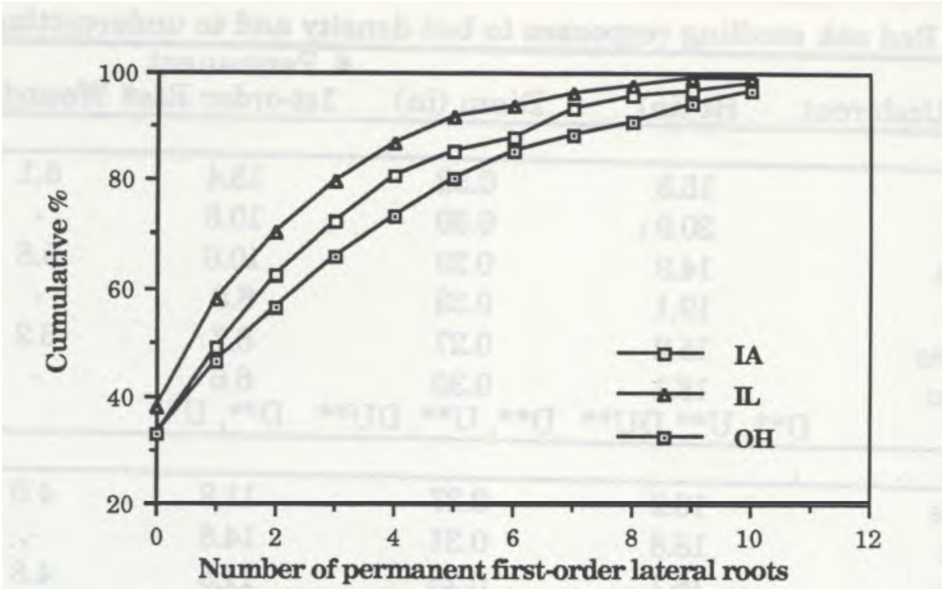


Figure 1A. Red oak permanent first-order lateral roots, 1-0, lifted spring, 1987.

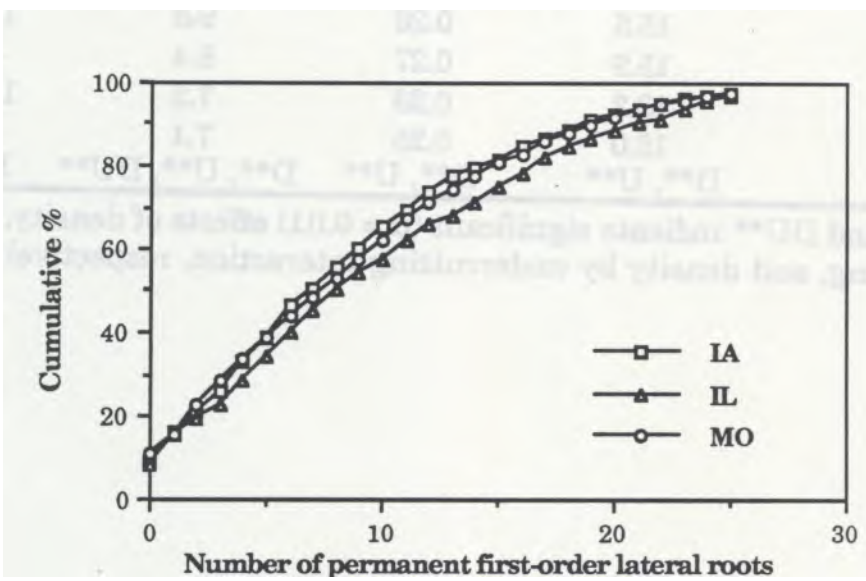


Figure 1B. Walnut permanent first-order lateral roots, 1-0, spring lifted, 1987.

Table 1. Red oak seedling responses to bed density and to undercutting.

Density/Undercut	Ht (in)	Diam (in)	# Permanent 1st-order Rts	# Wound Rts
Illinois				
3/ft^2- yes	15.3	0.32	13.4	6.1
3/ft^2 - no	20.9	0.39	10.8	-
6/ft^2 - yes	14.9	0.29	10.6	5.8
6/ft^2 - no	19.1	0.33	8.8	-
12/ft^2 - yes	15.2	0.27	8.7	6.2
12/ft^2 - no	18.1	0.30	6.6	-
	D**, U**,DU**	D**, U**, DU**	D**, U**	
Indiana				
3/ft^2 - yes	16.2	0.27	11.8	4.0
3/ft^2 - no	18.8	0.31	14.8	-
6/ft^2 - yes	16.1	0.25	11.5	4.8
6/ft^2 - no	17.3	0.26	12.4	-
12/ft^2 - yes	15.3	0.24	8.0	4.9
12/ft^2 - no	17.2	0.25	9.5	-
	D**, U**	D**, U**, DU**	D**, U**	D**
Ohio				
3/ft^2 - yes	16.2	0.30	14.3	2.2
3/ft^2 - no	17.8	0.30	12.0	-
6/ft^2 - yes	15.5	0.26	9.8	1.8
6/ft^2 - no	15.9	0.27	8.4	-
12/ft^2 - yes	13.2	0.23	7.2	1.3
12/ft^2 - no	15.0	0.25	7.1	-
	D**, U**	D**, U**	D**, U**, DU**	D**

D**,U**, and DU** indicate significant (a = 0.01) effects of density, undercutting, and density by undercutting interaction, respectively.

Table 2. Walnut seedling responses to bed density and to undercutting.

Density/Undercut	Ht (in)	Diam (in)	# Permanent 1st-order Rts	# Wound Rts
Illinois				
3/ft^2 - yes	22.9	0.40	14.4	4.0
3/ft^2 - no	35.0	0.46	10.7	-
6/ft^2 - yes	23.9	0.36	10.6	3.5
6/ft^2 - no	30.9	0.40	7.5	-
9/ft^2 - yes	23.3	0.36	8.6	3.2
9/ft^2 - no	30.3	0.39	6.6	-
	D**, U**, DU**	D**, U**	D**, U**	D**
Missouri				
3/ft^2 - yes	14.6	0.30	11.7	4.6
3/ft^2 - no	17.0	0.32	13.7	-
6/ft^2 - yes	15.9	0.28	8.8	4.1
6/ft^2 - no	18.3	0.30	9.8	-
9/ft^2 - yes	17.9	0.26	6.4	3.3
9/ft^2 - no	19.6	0.27	8.2	-
	D**, U**, DU**	D**, U**	D**, U**, DU**	D**

D**,U**, and DU** indicate significant (a = 0.01) effects of density, undercutting, and density by undercutting interaction, respectively.

Figures 2A and 2B show the total number of first-order lateral roots produced by different treatments. For both red oak and walnut, the undercut seedlings had greater numbers of total first-order permanent laterals than their uncut counterparts did. The increased number of roots resulted from the addition of two to six 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 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. At harvest, Iowa seedlings were lifted above the depth of undercutting, 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 Illinois density did not affect the number of wound roots produced by the undercutting

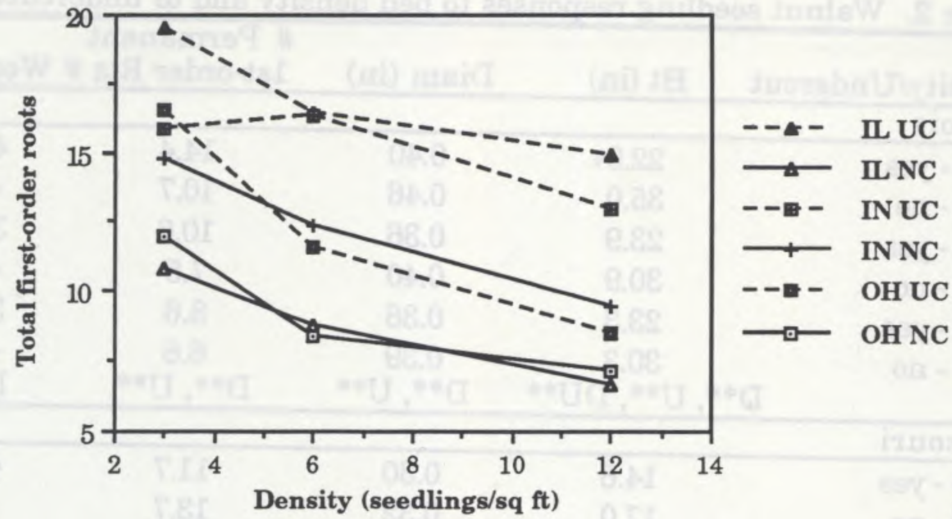


Figure 2A. **Red oak total first-order roots (first-order + wound roots), undercut (UC), and not cut (NC), 1-0, lifted spring, 1988.**

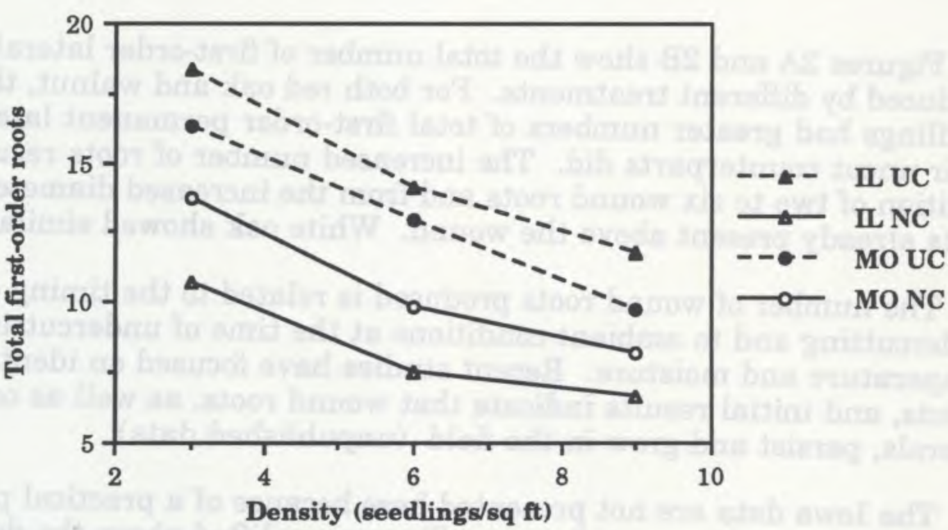


Figure 2B. Walnut total first-order roots (first-order + wound roots), undercut (UC), and not cut (NC), 1-0, lifted spring, 1988.

treatment . At all other states, however, 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/ft2.

Figures 3A and 3B and 4A and 4B show the cumulative distribution of red oak and walnut seedlings (%) by numbers of first-order lateral roots, for several states. White oak showed a response similar to the response of both red oak and walnut. In all cases, the undercut treatment produced, at a given density, more seedlings with greater numbers of total first-order lateral roots (first-order laterals + wound roots) than the uncut treatment did. The 3/ft^2 undercut treatment 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 in the Central States will produce more seedlings with increased potential for both survival and good early growth in the field.

Figures 5A and 5B for red oak and figures 6A and 6B for walnut show the relation between initial height and diameter (at time of lifting) and the total number of permanent, first-order lateral roots on seedlings. Although walnut shows very little height change with varying root numbers red oak shows a rapid increase in height as the number of laterals increases from five to eight. 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 seedlings that had been undercut and those that had not were usually less than 0.2 inches. Figures 5B and 6B 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 observe root system to distinguish whether it has five to six or more permanent first-order roots than to determine whether it has a 0.25 inch stem diameter.

Figures 7A-7C and 8A-8C show the responses of Illinois and Indiana walnut, respectively, to different dates and frequencies of undercutting. 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.

Height growth for Illinois walnut undercut during the month of June and the first week in July actually increased relative to that of uncut seedlings.

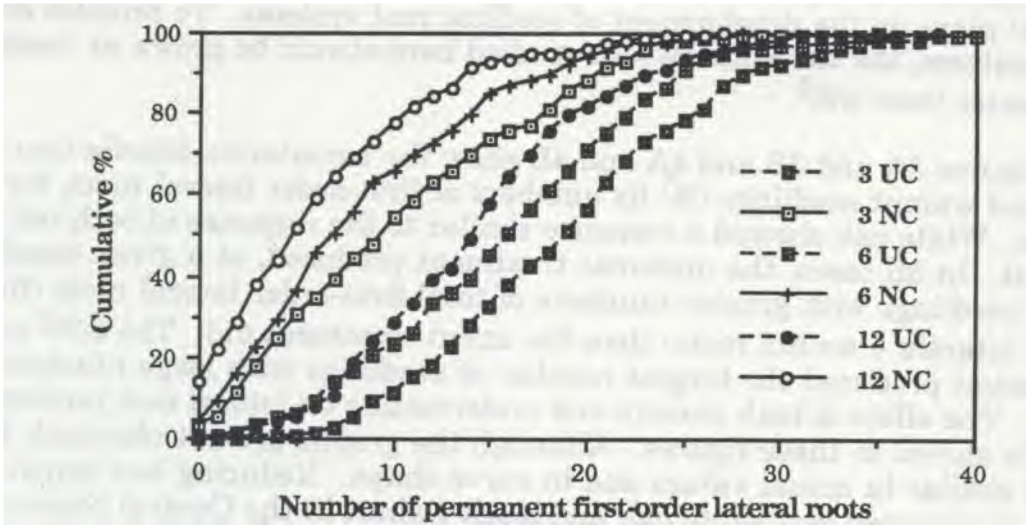
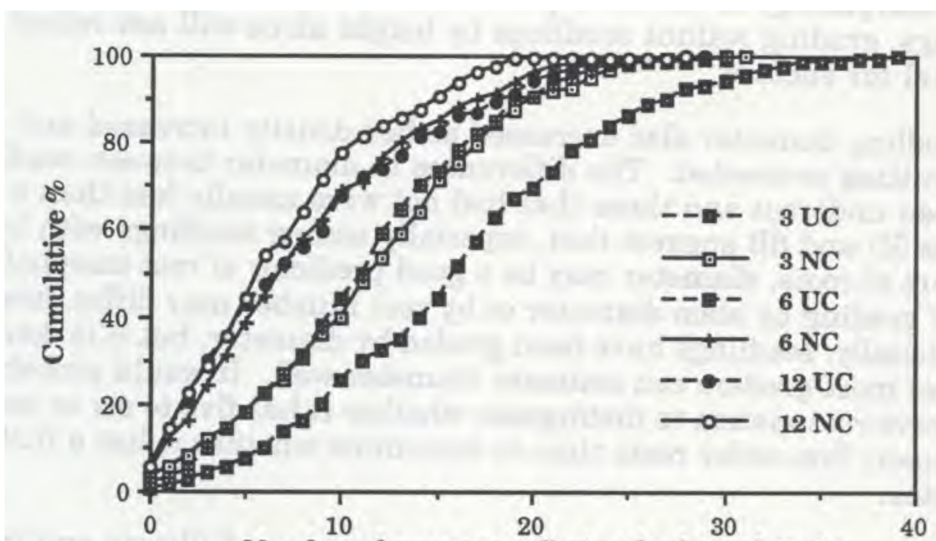


Figure 3A. % of IL, 1-0, red oak seedlings with 1st-order laterals, undercut (UC), not cut (NC), at 3, 6, 12 seedlings/sq ft, 1988.



igure 3B. % of OH, 1-0, red oak seedlings with 1st-order laterals, undercut (UC), not cut (NC), at 3, 6, 12 seedlings/sq ft, 1988.

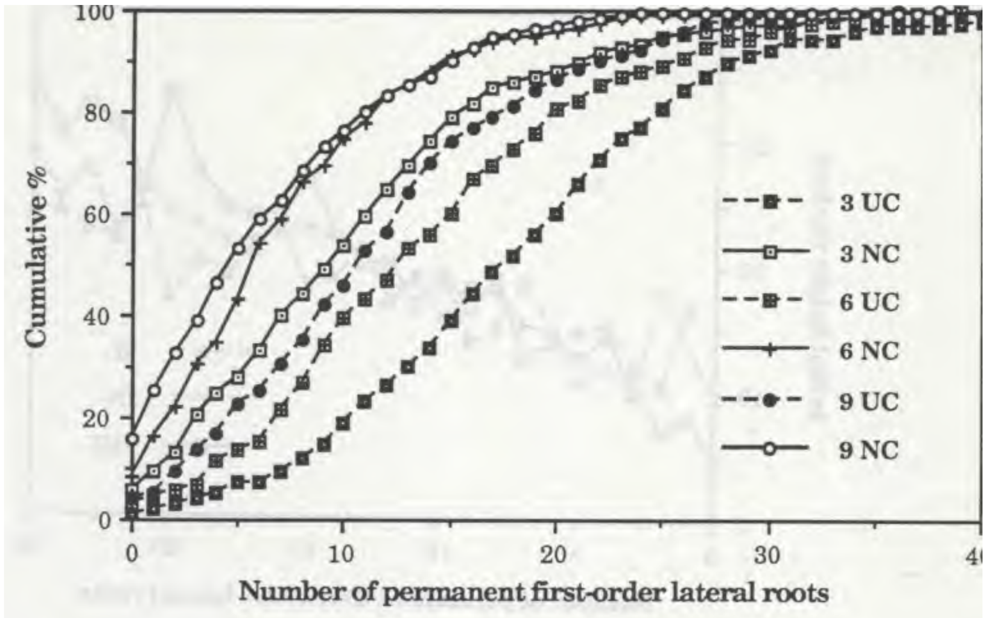


Figure 4A. % of Illinois, 1-0, walnut seedlings with 1st-order lateral roots,undercut (UC), not cut (NC), at 3, 6, 9 seedlings/sq ft, 1988.

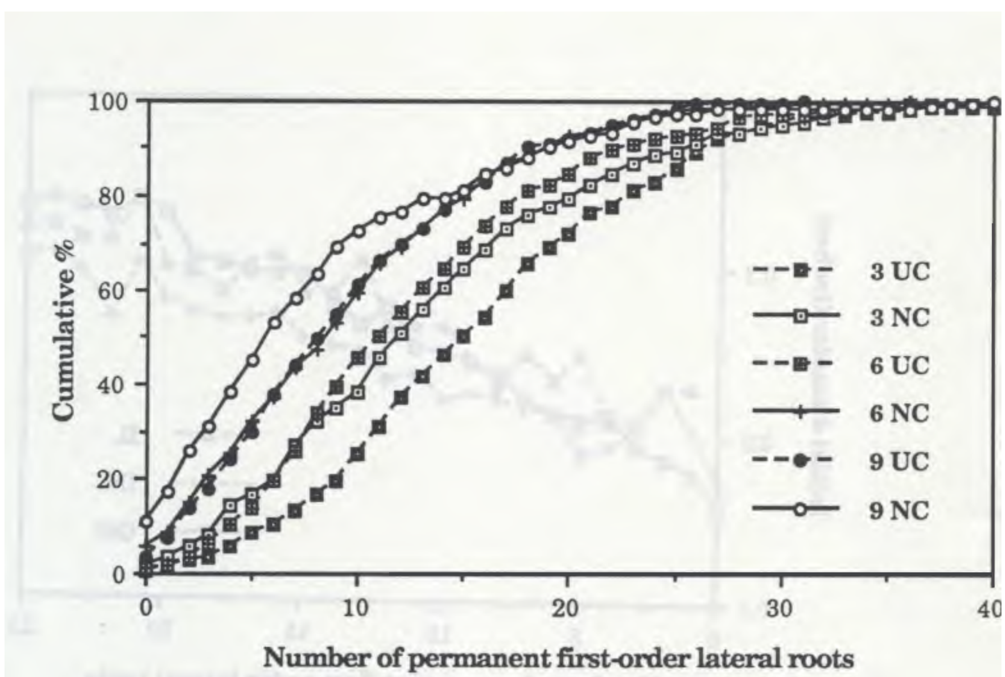


Figure 4B. % of Missouri, 1-0, walnut seedlings with 1st-order lateral roots undercut (UC), not cut (NC), at 3, 6, 9 seedlings/sq ft, 1988.

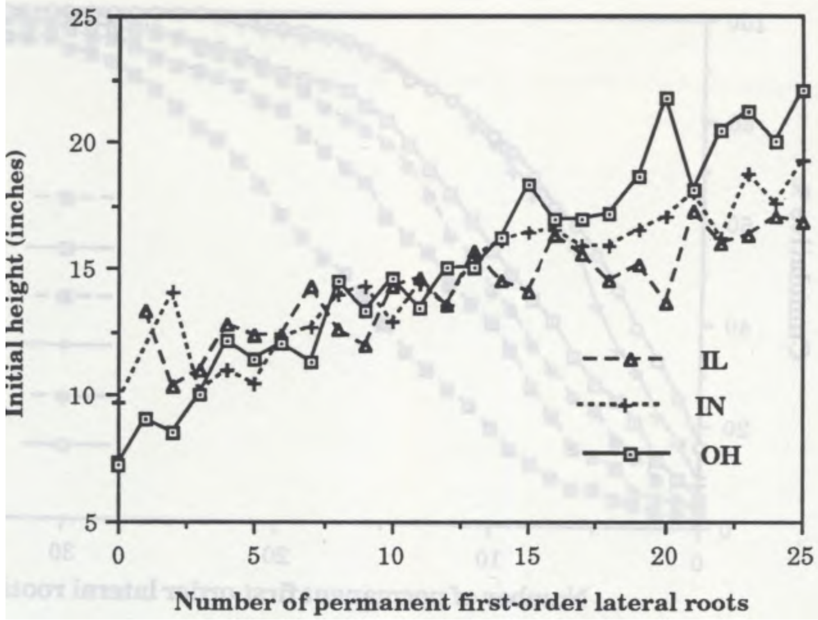


Figure 5A. Initial height vs total 1st-order laterals, of 1-0 red oak seedlings grown at three densities, lifted spring, 1988.

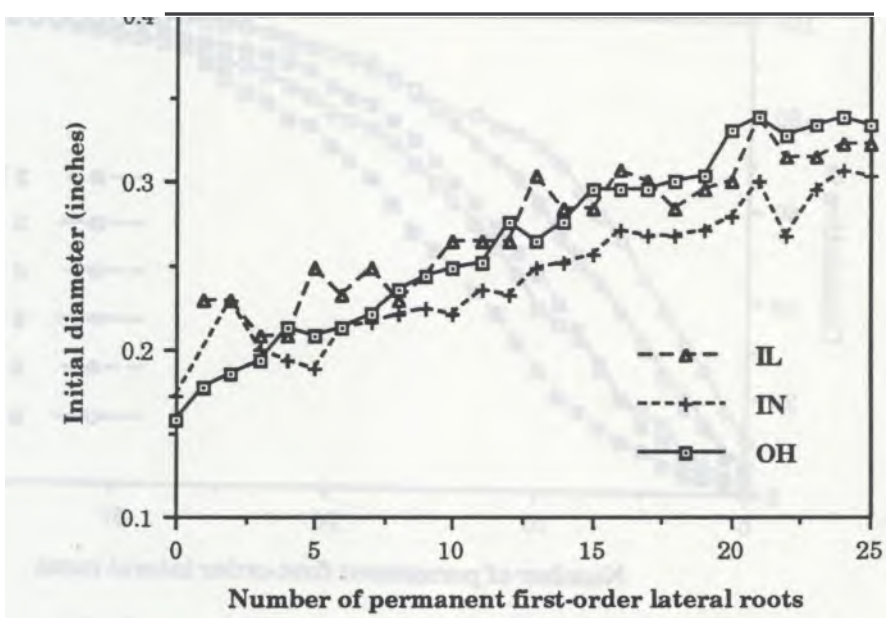


Figure 5B. Initial diameter vs total 1st-order laterals, of 1-0 red oak seedlings grown at three densities, lifted spring, 1988.

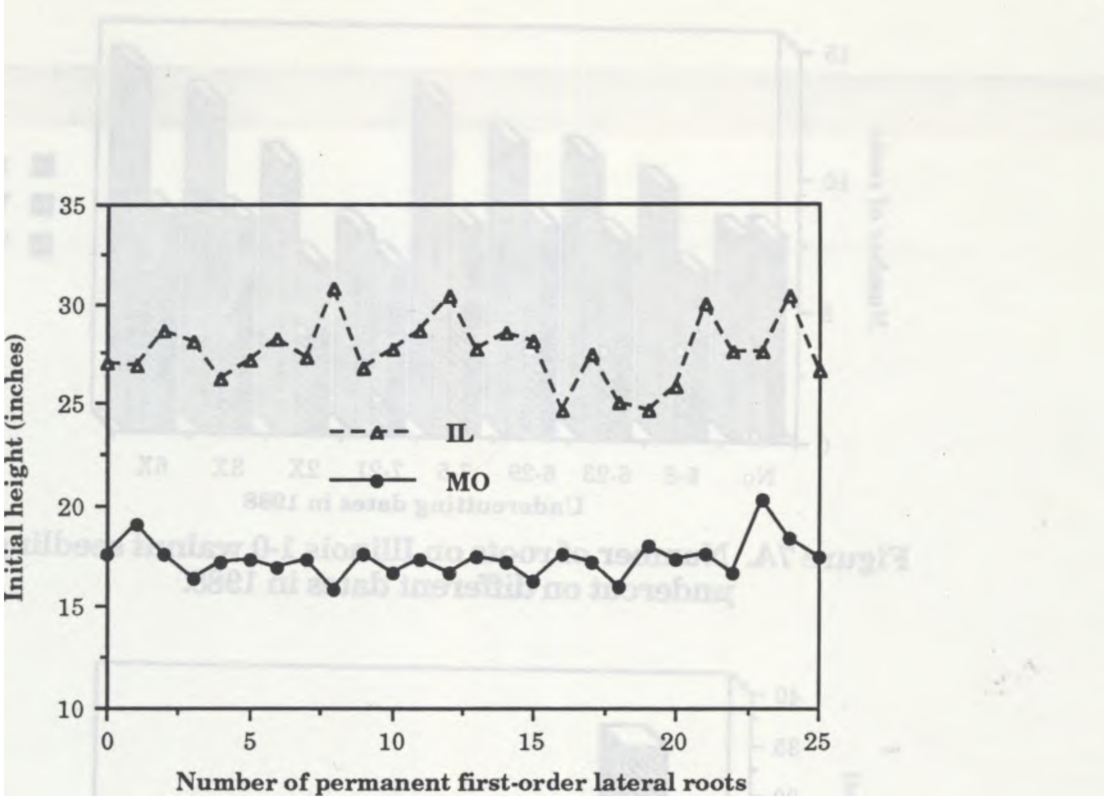


Figure 6A. Initial height vs total 1st-order laterals, of 1-0 walnut seedlings grown at three densities, lifted spring, 1988.

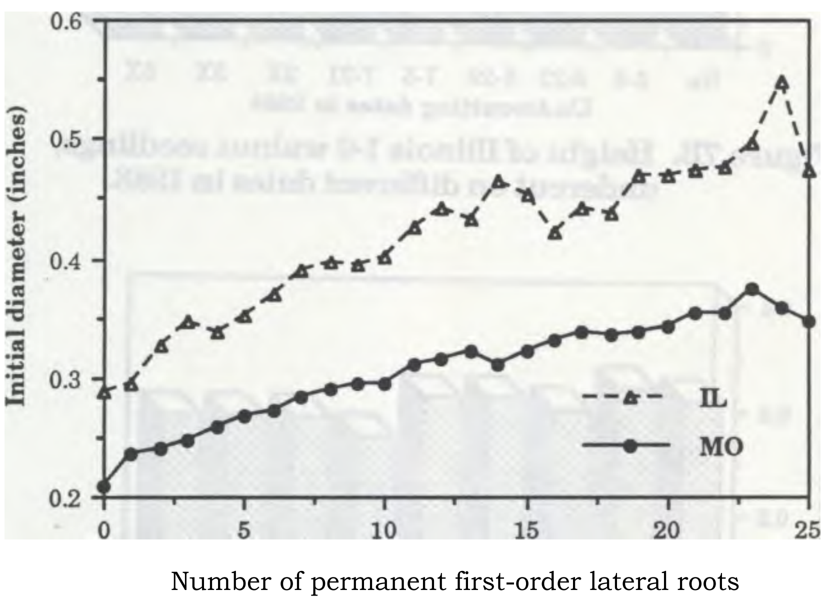


Figure 6B Initial diameter vs total 1st-order laterals, of 1-0 walnut seedlings grown at three densities, lifted spring, 1988.

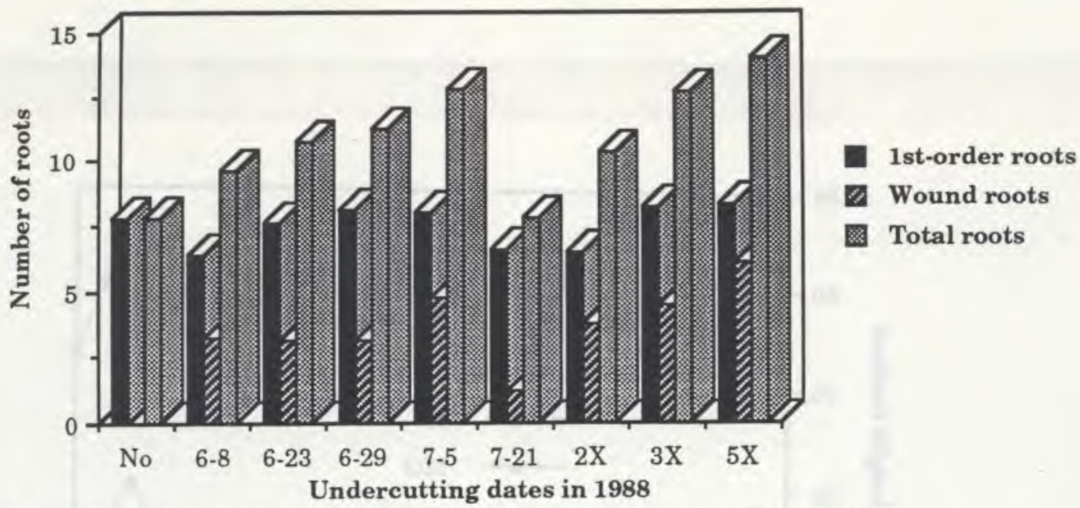


Figure 7A. Number of roots on Illinois 1-0 walnut seedlings, undercut on different dates in 1988.

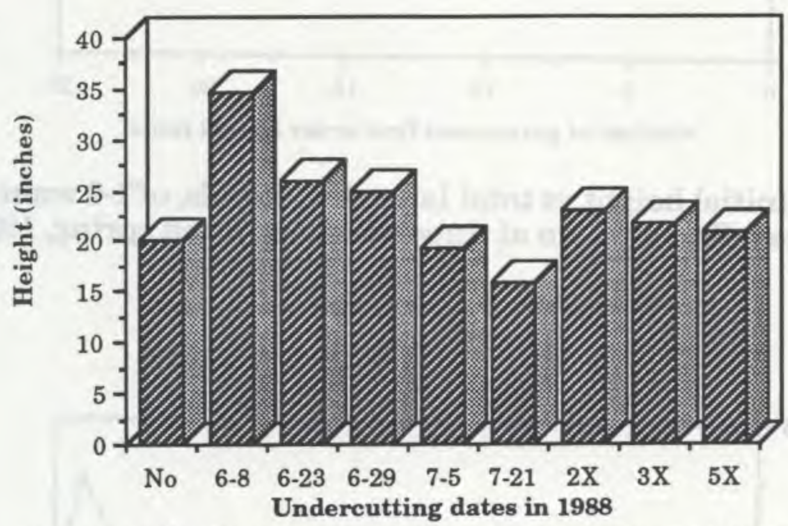


Figure 7B. Height of Illinois 1-0 walnut seedlings, undercut on different dates in 1988.

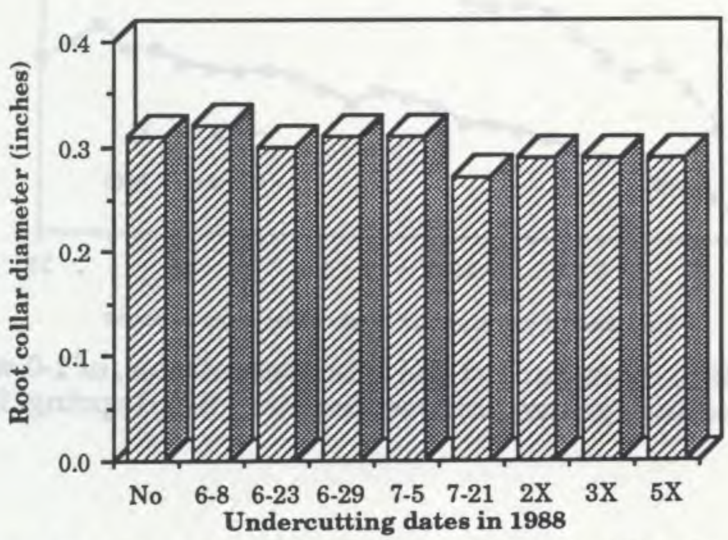


Figure 7C. Root collar diameter of Illinois 1-0 walnut seedlings, undercut on different dates in 1988.

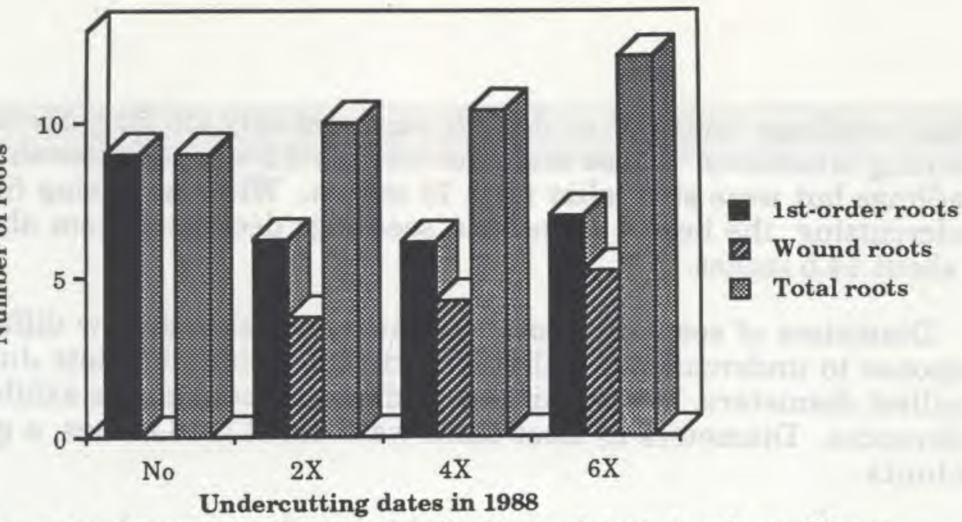


Figure 8A. Number of roots on Indiana 1-0 walnut seedlings, undercut on different dates in 1988.

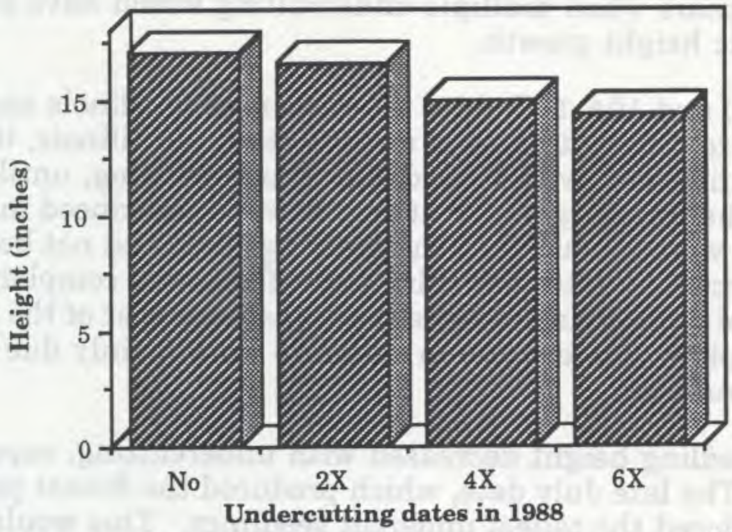


Figure 8B. Height of Indiana 1-0 walnut seedlings, undercut on different dates in 1988.

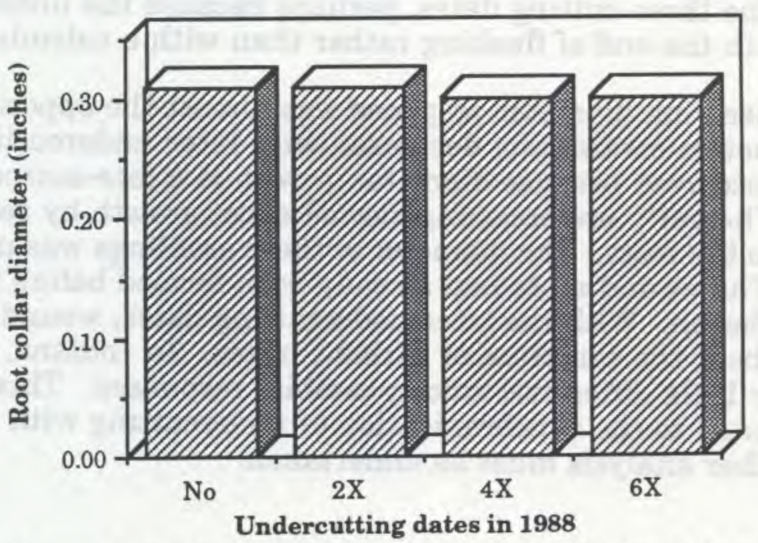


Figure 8C. Root collar diameter of Indiana 1-0 walnut seedlings, undercut on different dates in 1988.

Those 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. With increasing frequency of undercutting, the height of Indiana seedlings decreased from about 17 inches to about 14.5 inches.

Diameters of seedlings from both nurseries showed few differences in response to undercutting. Illinois seedlings undercut in late July had the smallest diameters, but remaining seedlings in both states exhibited few differences. Diameters in most cases were about 5/16 inches, 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 does not seem necessary to use multiple undercuts unless there is a height growth problem. This recommendation is based on data from only one year and could change depending on the weather. There have been years when multiple undercutting would have been necessary to reduce dramatic height growth.

Figures 9A-9C and 10A-10C show the responses of Illinois and Indiana red oak, respectively, to different dates of undercutting. In Illinois, the number of permanent roots increased with later dates of undercutting, until late July (July 27). Even the late July undercutting, however, produced more permanent lateral roots than were produced on the seedlings that had not been undercut. In Indiana, undercutting after the third shoot flush was complete produced slightly fewer total roots than did undercutting after either of the first two flushes were complete. Differences in response were mainly due to a decrease in wound roots produced.

In Illinois, 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 directed to shoot growth before redirection occurs. In Indiana, there were no differences in height growth among the three cutting dates, perhaps because the undercutting was synchronized with the end of flushing rather than with a calendar date.

In Illinois, seedling diameter response was almost the opposite of height response. Diameters continually decreased with later undercutting dates. This may have occurred because diameter growth is a late-season phenomenon. The early undercutting slowed shoot growth by redirecting carbohydrates to the roots. The diameter of these seedlings was not affected by undercutting. The wound roots had already been formed before major cambial growth activity began. With the later undercutting dates, wound root production "robbed" the cambium of carbohydrates. In Indiana, there was, once again, very little difference among cambial responses. This response may somehow be related to the synchronization of undercutting with flushing pattern but further analysis must be undertaken.

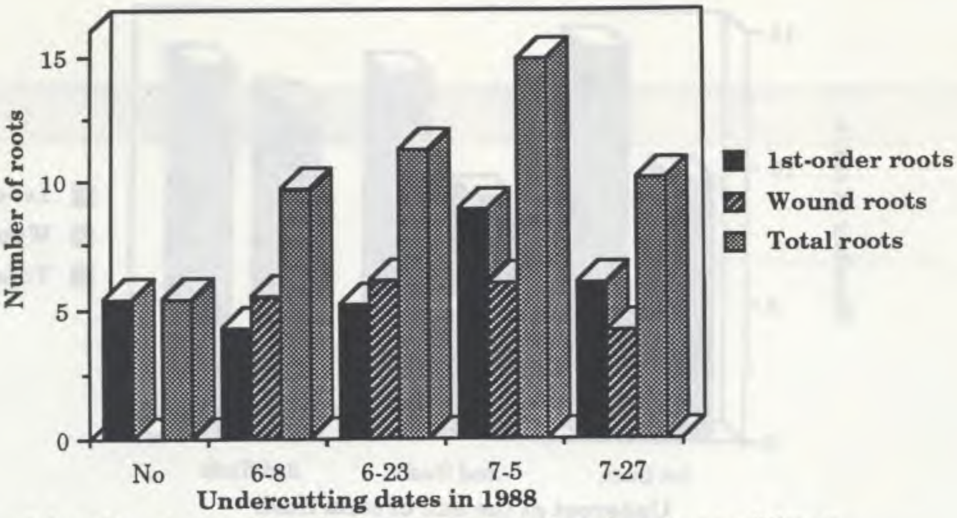


Figure 9A. Number of roots on Illinois 1-0 red oak seedlings, undercut on different dates in 1988.

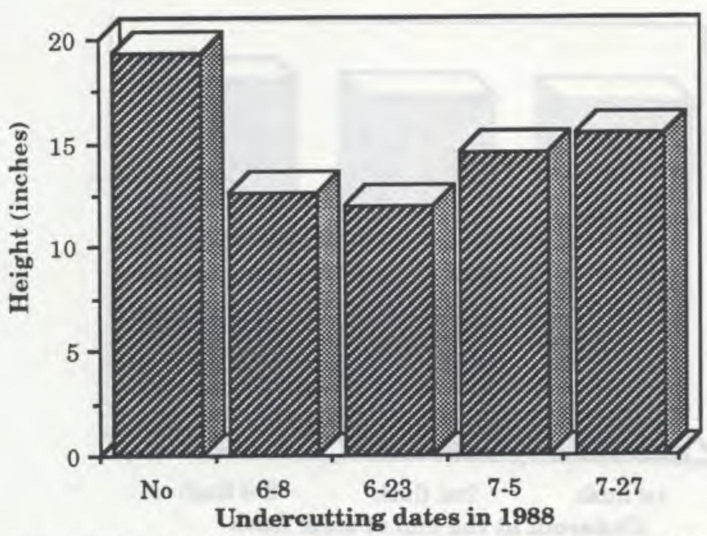


Figure 9B. Height of Illinois 1-0 red oak seedlings, undercut on different dates in 1988.

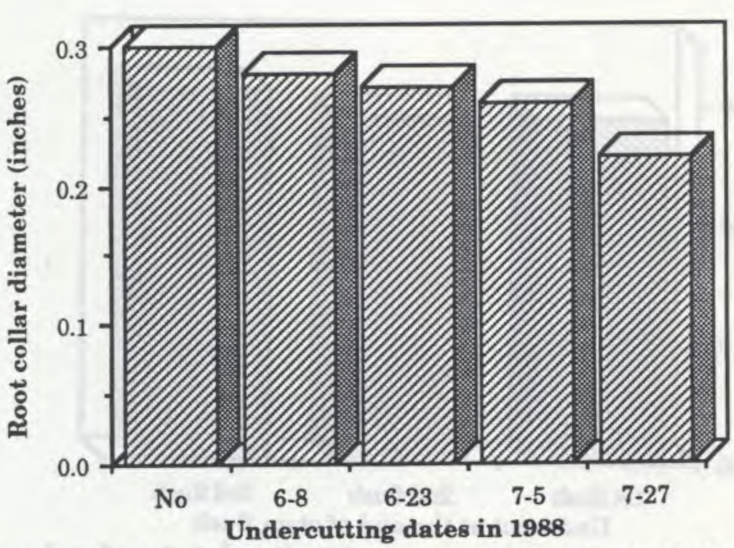


Figure 9C. Root collar diameter of Illinois 1-0 red oak seedlings, undercut on different dates in 1988.

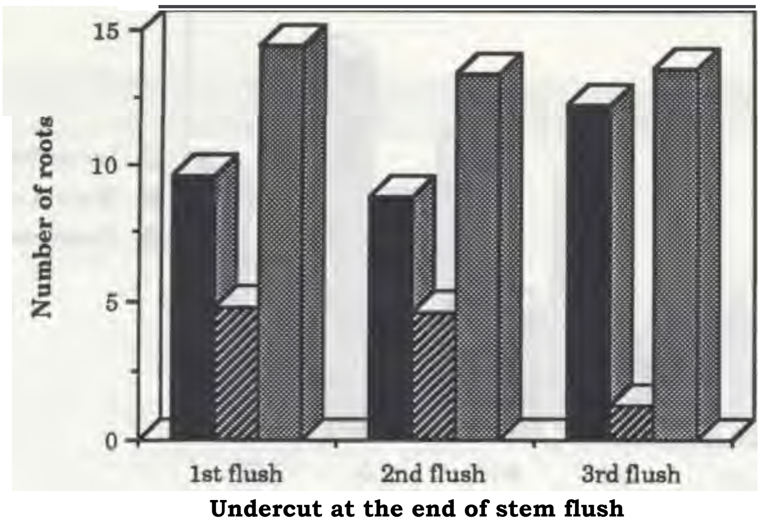


Figure 10A. Number of roots on <u>Indiana</u> 1-0 red oak seedlings, undercut after the 1st, 2nd, or 3rd stem flush in 1988.

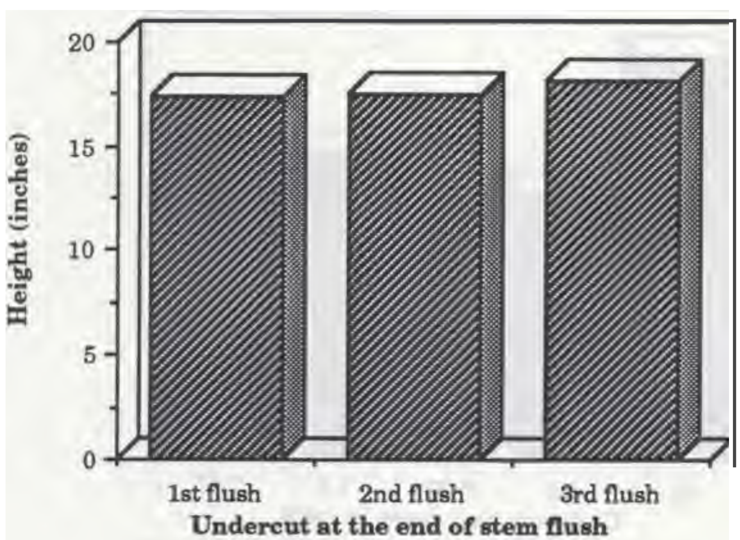


Figure 10B. Height of Indiana 1-0 red oak seedlings, undercut after the 1st, 2nd, or 3rd stem flush in 1988.

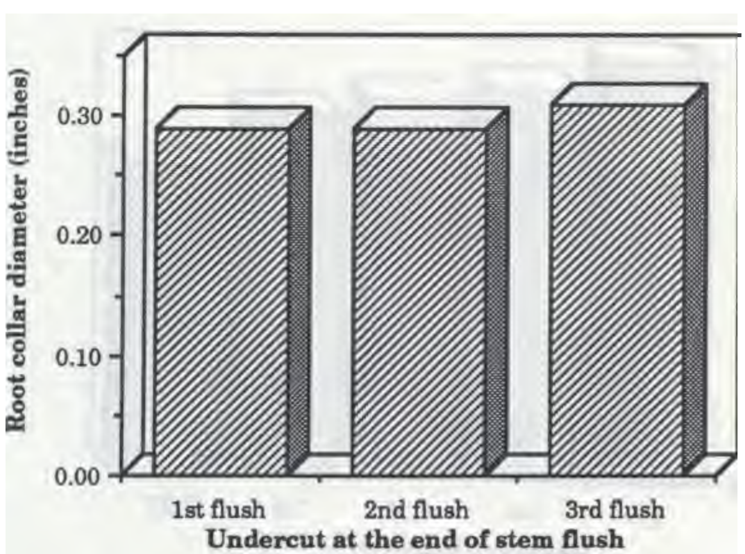


Figure 10C. Root collar diameter of Indiana 1-0 red oak seedlings, undercut after the 1st 2nd or 3rd stem flush in 1988.

According to observations made during the summer of 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, undercutting should be done when the terminal bud has stopped expanding and the uppermost leaves have expanded to about 3/4 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 three to four weeks are needed for wound roots to be initiated, and that another three weeks are needed for those roots to become suberized and therefore 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. It is difficult to control undercutting depth precisely in a nursery bed because of uneven bed heights and soil densities. It should be possible to control depths to within 2 inches above or below the target depth. Lifting depths are usually not deeper than 10 - 12 inches. As a result, undercutting should be done at a depth of 6-8 inches. If lifting is done at shallower depths, undercutting also should be.

Ideally, the weather for undercutting should be cool and moist. Such conditions are unlikely in late June to mid-July. It is therefore important for seedlings to be well irrigated no more than a day before undercutting. Undercutting should be done between 6 am and 10 am or in the evening after 7 pm. Seedlings should be irrigated again immediately after undercutting. It would be unwise to undercut when temperatures are expected to exceed 90° F.

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

Figures 11A-11C and 12A-12C show the results of the mother-tree progeny tests for red oak in Missouri and for walnut in Iowa, respectively. These graphs show that there is much variation among seed sources in terms of root numbers produced and associated height and diameters. At this point, we feel that 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.

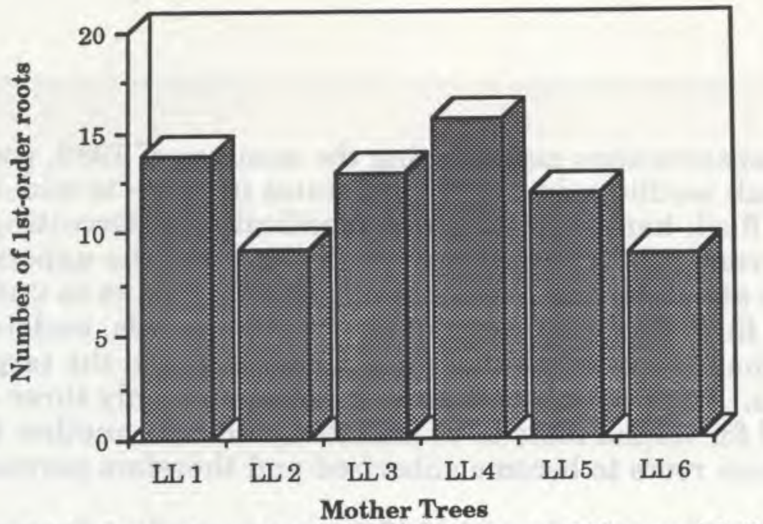


Figure 11A. Number of 1st-order roots on Missouri 1-0 red oak seedlings from different mother trees, 1988.

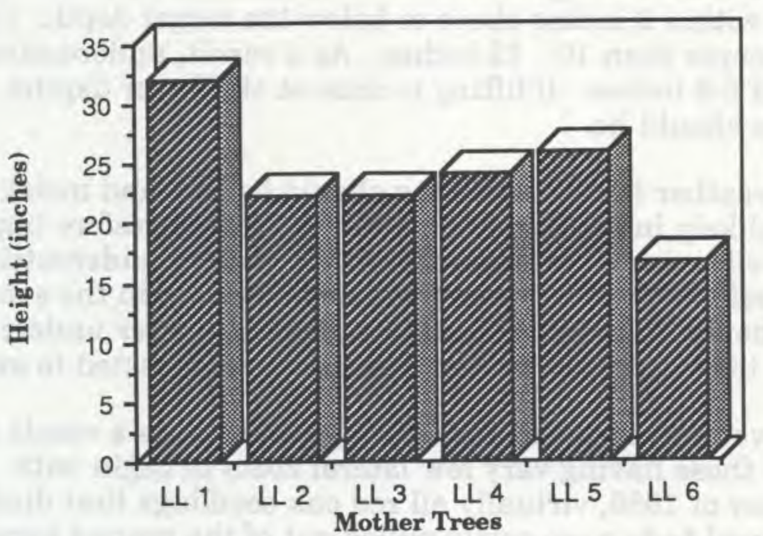


Figure 11B. Height of Missouri 1-0 red oak seedlings from different mother trees, 1988.

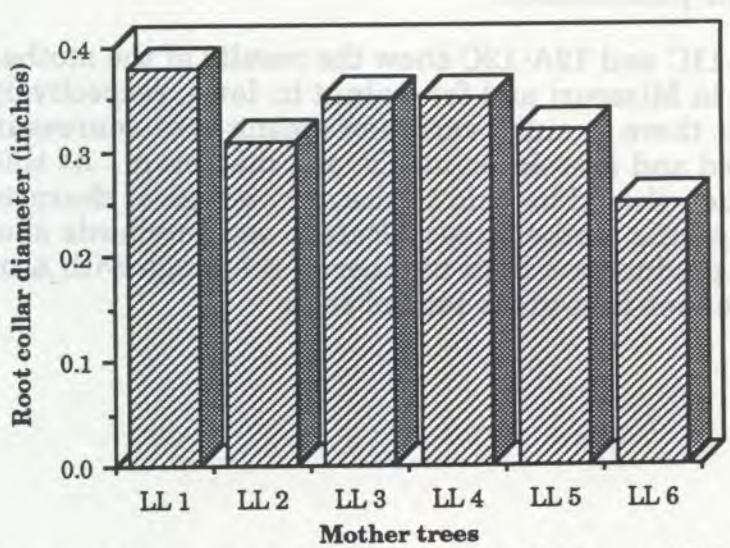


Figure 11C. Root collar diameter of Missouri 1-0 red oak seedlings from different mother trees, 1988.

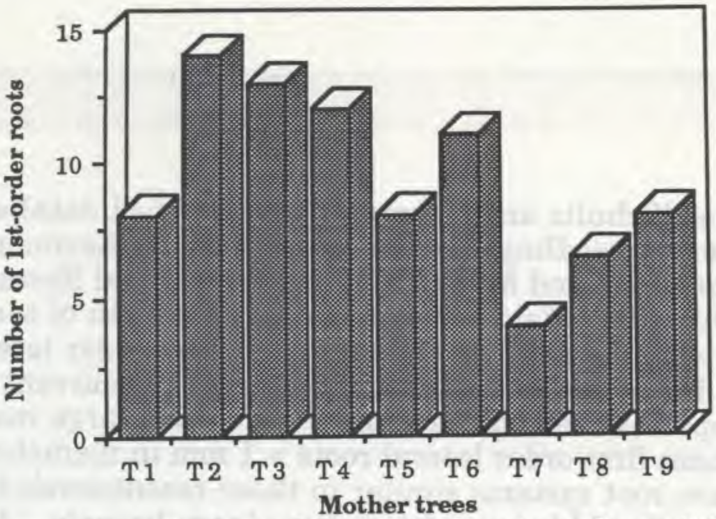


Figure 12A. Number of 1st-order roots on Iowa 1-0 walnut seedlings from different mother trees, 1988.

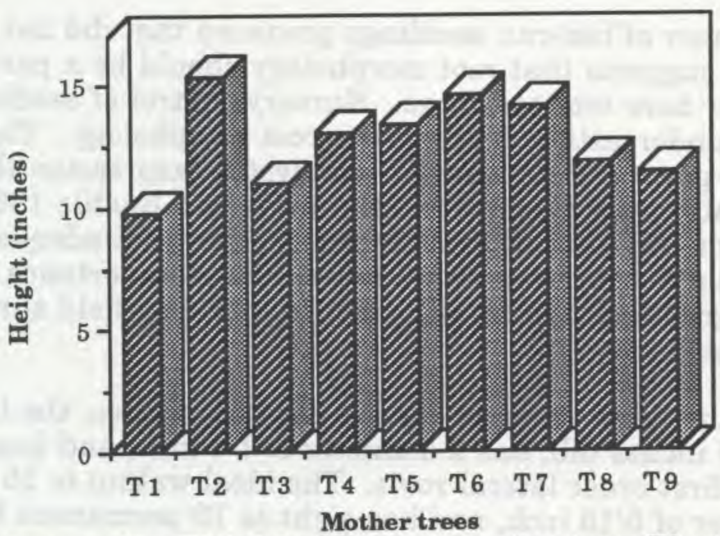


Figure 12B. Height of Iowa 1-0 walnut seedlings from different mother trees, 1988.

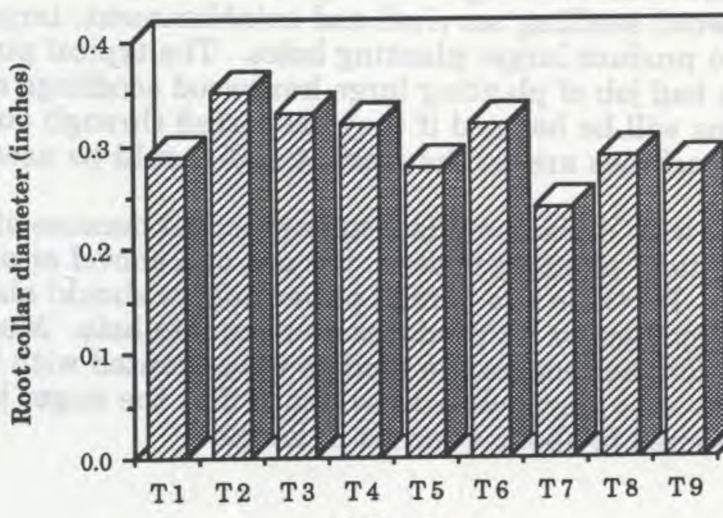


Figure 12C. Root collar diameter of Iowa 1-0 walnut seedlings from different mother trees, 1988.

Summary

In certain studies (Schultz and Thompson unpublished data) of the outplanting of numerous seedlings and in recent work by Kormanik and others (Kormanik 1986, Kormanik and Muse 1986, and Ruehle and Kormanik 1986, Kormanik and Ruehle 1987), 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 the current study suggests that a competitive 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 this study, after two years in the field, seedlings having these 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 did.

The large number of bed-run seedlings produced that did not meet these minimum criteria suggests that root morphology should be a part of the grading scheme for bare-root seedlings. Nursery control of seedbed density and the use of timely undercutting can improve root morphology. There is, however, a strong genetic component to root system expression that will require grading to eliminate root system culls (Kormanik and Ruehle 1986). 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 - 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 - 20 inches tall, has a diameter of 5/16 inch, and has eight to 10 permanent first-order lateral roots.

Such large hardwood seedlings will require new approaches to planting. To improve hardwood seedling survival and establishment, larger equipment will be required to produce larger planting holes. The typical pine planting machine will do a bad job of planting large hardwood seedlings and many of the larger root systems will be harmed if they are forced through such planters. Larger planting machines are on the market and should be used.

Hand planting with dibble bars is also impractical because of the size of the hole produced. If hand planting is done, the use of a shovel or a large hodag might be required. Portable two-person power augers should also be considered. 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 trimmed to about 4 inches in length.

If high-quality hardwood plantations are to be successfully established, large seedlings with well-developed permanent first-order root systems are required and must be planted with the **proper equipment.**

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