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Half-sib seed source and nursery sowing density affect black walnut (*Juglans nigra*) growth after 5 years

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Abstract The effect of seed source (half-sib family) and nursery bed density on the nursery stock quality and subsequent growth of black walnut (*Juglans nigra* L.) was investigated. Nine black walnut female genitors were selected to represent a range of phenotypes. Seeds were collected, cleaned, cold-treated, and pre-sprouted to ensure that germination was uniform and complete. The pre-sprouted seeds were planted in a randomized complete block design into standard nursery beds in Indiana, USA at three sowing densities, (11.2 plants m^{-2}; 24.2 plants m^{-2}; 29.4 plants m^{-2}). After lifting, the trees were measured for height, ground-line diameter and root volume and then planted into a plantation in a randomized complete block design and re-measured after 1 and 5 years of growth. One year after planting, the effects of family (half-sib seed source) and density were significant or very highly significant for seedling height, and ground-line diameter, although family effects were greater than those for density, especially at moderate and high nursery bed density. After 5 years of growth, the same effects contributed significantly to ground-line diameter and dbh, but only family significantly influenced height. Family was more important than nursery bed density in determining the size of the trees after 5 years. Although there were no significant family × density interactions after 5 years, family variance for all the traits was considerably higher among seedlings grown at moderate and high density in the nursery. Phenotypic correlations among traits within and among years were generally very high ($0.65 < r < 0.90$) and insensitive to planting density in the nursery.

Keywords Seedling quality · Root volume · Shoot height · Ground line diameter · Hardwood genetics · Bareroot nursery production

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Introduction

Black walnut (*Juglans nigra* L.) is an important component of forests in the Central Hardwood Region (CHR) of the USA, producing valuable timber and nut resources (Williams 1990; Shifley 2004). Black walnut seedlings are used for afforestation plantings and, to a lesser extent, as a rootstock for grafting genetically improved germ plasm, making black walnut among the most common species grown in forest tree nurseries in this region (Jacobs et al. 2004). Planted hardwood seedlings often grow poorly or fail to survive (Jacobs et al. 2004), which may be partially attributed to variability in nursery stock quality. Morphological attributes such as shoot height and stem diameter are easily measured and often used to evaluate nursery stock quality (Thompson 1985; Dey and Parker 1997). In addition, root volume and root system morphology such as number of first order lateral roots are useful measures of hardwood seedling performance (Schultz and Thompson 1996; Dey and Parker 1997; Jacobs et al. 2005a, b). The linkage between nursery stock quality and field performance is still a matter of research for hardwoods in the CHR (Mohammed 1996; Wilson and Jacobs 2006), but stock quality is associated with growth over the long term for at least some conifer species (South et al. 1985; Newton et al. 1993).

Black walnut nursery stock quality is primarily controlled through nursery cultural practices (Jacobs 2003). Bed sowing density is among the most important variables influencing stock quality. Larger seedlings are consistently produced at relatively low sowing densities (Schultz and Thompson 1996). Low seedbed densities, however, limit overall nursery stock production, as fewer seedlings are produced in a fixed amount of bed space. In the CHR of the USA, nursery production often fails to keep pace with demand, especially for valuable hardwood species such as black walnut (Michler and Woeste 2002). In addition, survival of planted seedlings is typically only about 60% (Jacobs et al. 2004). Thus, an examination of factors that might enhance nursery stock quality to improve the survival and growth of black walnut nursery stock after planting is warranted. Alternatively, changes in production methods that permit planting stock of acceptable quality to be grown at higher planting densities might permit an expansion of nursery production without need of additional space.

Although extensive literature exists on the genetic improvement of black walnut as a plantation tree (Beineke 1989; Victory et al. 2004), relatively little attention has been paid to the role of genetics in determining the stock quality of nursery seedlings or the interaction of genetics with current nursery practices. Most black walnut nursery stock is grown from seeds of unknown or undocumented provenance (Jacobs and Davis 2005), limiting the potential of genetics as a tool to improve black walnut nursery stock quality. Thus, the objective of this study was to examine the relative role of half-sib seed source and nursery sowing density in the growth of black walnut nursery stock and subsequent performance in an afforestation plantation. We also sought to determine the potential benefits to nursery managers from controlling the genetics of seed sources.

Materials and methods

In October 2002, seeds were collected from eleven open-pollinated black walnut trees in Indiana, USA. The families were chosen to represent a wide range of growth phenotypes (see below and Table 1). The seeds were harvested from the ground soon after they abscised, they were then hulled, washed, and air dried. In early December, 2002, the seeds

Table 1 Phenotypes of seed sources for half-sib families planted in 2004

Family identifier	Location and type of seed source[a]
A	Fence-row tree, crooked, highly branched, slow growth
B	Pasture, wild, large diameter, large spreading limbs
C	Forest, tall, straight, high quality (wild) tree
D	Selected for nut production, spreading habit, average growth rate
E	HTIRC, 2nd generation selection, straight, strong leader
F	HTIRC, 1st generation selection, high veneer quality, straight
H	HTIRC, 2nd generation selection, rapid growth
I	1st generation selection, discarded after testing, slow growth
J	Check from progeny test, average growth and form

[a] HTIRC = Hardwood Tree Improvement and Regeneration Center, Purdue University

were rinsed, mixed with damp sphagnum peat moss (2:1 W/W moss:water), and placed into cold storage at 4°C for 90 days of stratification.

Seeds were planted as pre-sprouted seedlings (Davis et al. 2004) to ensure that each plot of the density treatments had the correct number of plants. In order to pre-sprout the seeds, in February, 2003, they were sown in plastic flats with Scotts Metro-Mix 360® with Coir growing media (O.M. Scotts Co., Marysville, OH, USA) and placed into a greenhouse. Greenhouse environmental conditions were maintained at 24/17°C (day/night) with natural photoperiod and ambient light intensity. The flats were watered as necessary to maintain moist media. Twice weekly, the seeds from each flat were carefully rinsed free of planting media, and sprouted seeds were removed when the radicle was two to six mm in length. All other seeds were returned to flats as described above until enough sprouted seeds of each family were obtained. The sprouted seeds were refrigerated at 4°C until a sufficient number had been collected for all families, at which time they were planted at the Indiana Department of Natural Resources Forestry Nursery in Vallonia, Indiana, USA (38°48′N, −86°06′W). By planting pre-sprouted seeds, we ensured that all seedlings, irrespective of family, and that all families, irrespective of emergence time or rate, began growth and competition uniformly in the nursery bed.

Sprouted seeds from each family were sown by hand into bareroot nursery bed plots at three sowing densities (11.2 plants m^{-2}; 24.2 plants m^{-2}; 29.4 plants m^{-2}) on two consecutive days in April, 2003. Density and spacing were kept consistent and uniform by modifying plywood boards into planting jigs. The boards, which contained wooden dowels spaced at regular intervals, were lowered onto the nursery bed, producing holes in the soil at the desired spacing for each density. Seeds were planted in a grid pattern, not in rows. Low density plots (L) were 2.85 m^2 (32 seeds, 29.8 cm between seedlings), medium density (M) plots were 1.24 m^2 (30 seeds, 20.3 cm between seedlings), and high density (H) plots were 1.02 m^2 (30 seeds, 18.4 cm between seedlings). Plots were arranged in the nursery beds in a randomized complete block design consisting of four blocks, where every block contained plots for each family × density combination. The planted nursery plots were covered with woven wire fencing to prevent predation by squirrels, but otherwise the seedlings were grown under operational nursery conditions (Jacobs 2003) until lifting in March, 2004. After lifting, seedlings were stored at 2°C until they were measured for morphological characteristics including stem diameter, shoot height, and root volume using the water displacement method of Burdett (1979). All the seedlings from the plots were lifted, but only seedlings from the interior of the plots were transplanted; border seedlings were not used subsequently in the study. Block structure from the nursery was not retained in the subsequent planting; seedlings of each family × density combination were pooled, mixed and randomly assigned to plots as described below. There were insufficient numbers of seedlings from two families for the next stage of the experiment, so only nine families were planted out (Table 1).

The subsequent study of tree growth was established April 7, 2004 at the Southeast Purdue Agricultural Center (SEPAC), located in Jennings County, southeastern Indiana, USA (N 39°2′, W-85° 30′). The soil at the study site was a Park series (fine-silty, mixed, active, mesic, Ultic Hapludalf) with less than 1% organic matter and 6.5 pH. The site was a cornfield in the previous year; it was not tilled prior to planting, but it was broadcast with 1.0% glyphosate. After planting, and annually, weed control was achieved with a mixture of the herbicides Princep^{TM} [6-chloro-N_2,N_4-diethyl-1,3,5-triazine-2,4-diamine] at a rate of 7 l ha^{-1}, and Pendulum Aqua Cap^{TM} [N-(1-ethylpropyl)-3,4,-dimethyl-2,6-dinitrobenzenamine] at a rate of 3.4 kg ha^{-1}, applied in 0.9 m wide strips down the row. Trees were planted as 1–0 bare-root seedlings in augured holes on a 2.4 × 2.4 m grid, and fenced to reduce herbivory by white tailed deer (*Odocoileus virginianus*). During planting, diseased or damaged trees were discarded. Trees were planted in eight blocks; each block contained 27 randomized, four-tree plots (nine families × 3 nursery densities). Survival was 97% after 5 years. Measurements of height, ground line diameter (gld), and root volume were made in 2003 prior to planting, and extremely small trees (root collar diameter < 5 mm) were discarded in accordance with recommended practice in the region. Height and ground-line diameter were measured after cessation of growth in 2004 and 2009, and diameter at 1.5 m (dbh) was also measured in 2009. In 2004 and 2009, seedlings were rated subjectively for potential to grow to a crop tree using a 1–5 scale ($1 =$ crooked, highly forked, multi-stemmed, branchy; $5 =$ straight, self-pruning, and possessing a single, dominant, central stem), and presence of a dominant terminal shoot (±).

All analyses were performed using SAS 9.1 (SAS Institute Inc., Cary NC, USA). Multivariate analysis of variance was performed using a generalized linear mixed model (Proc Mixed or GLIMMIX), where dbh, shoot height, root volume, and ground line diameter were dependent variables, and family, sowing density, block, family × density, block × density, and family × block interactions were independent variables. Root volume was analyzed based on plot means in the nursery. For all variables measured in 2004 and 2009, observations were plot means; plots were four seedlings of a single family grown in the nursery at one of three densities. Measurements in 2003 included trees that had been border trees in the nursery plots. At lifting in 2003, 1351 trees were measured, but only about 840 were subsequently planted at SEPAC because culls and border trees were eliminated. To test each effect in Proc Mixed, we used the Kenward-Roger method to estimate degrees of freedom. This method can produce fractional degrees of freedom when observations are missing. We compared density, family and family × density as fixed effects, using block, block × density and block × family as random effects. When comparing density treatments only (Table 2) we considered density to be the only fixed effect and considered family, block and interaction effects to be random. For each dependent variable, the least-squares means and standard deviations were generated by invoking LSMEANS. Density treatments (Table 2) were compared using a *t*-test with $\alpha = 0.05$. Components of variance were generated using PROC VARCOMP and methods described previously (Woeste 2002), where block was considered a fixed effect, and all other

Table 2 Size of black walnut seedlings planted at three nursery bed densities

Nursery density[a]	2003			2004		2009		
	Height (cm)[b]	Ground-line diameter (mm)	Root volume (cm^3)	Height (cm)	Ground-line diameter (mm)	Height (cm)	Diameter (DBH) (mm)	Ground-line diameter (mm)
Low	37.4b	12.2a	142a	124.6a	26.7a	228a	20.5a	49.4a
(range)[c]						(211–261)	(19.0–25.1)	(44.3–54.2)
Medium	46.6a	11.7a	105b	116.5b	24.2b	215a	18.1b	45.6b
(range)						(189–233)	(15.7–21.0)	(40.9–51.7)
High	51.3a	10.6b	84c	117.5b	23.8b	217a	18.3b	45.7b
(range)						(201–243)	(16.3–20.0)	(41.5–49.3)
Mean	45.6	11.5	110.3	119	25.0	220	19.3	47.0

[a] Low density (11.2 seeds m^{-2}), medium (24.2 seeds m^{-2}), high (29.4 seeds m^{-2})

[b] Means followed by the same letter are not significantly different, alpha = 0.05, for details, see Materials and Methods

[c] Range of family means for each trait for seedlings grown at the indicated bed density

variables were considered random. Simple correlations (Pearson) and rank correlations (Spearman) among the response variables were estimated using PROC CORR, the effect of density and family on seedling quality was tested using Chi square in PROC NPAR1WAY.

Results

Growth in the nursery and after 1 year at SEPAC

At lifting, after the 2003 growing season, seedlings grown in low density nursery plots had the largest ground line diameter (GLD), largest root volume (RV), and smallest height (Table 2). The root volume of seedlings grown in the low density nursery plots averaged about 142 cm^3, 65% greater than the seedlings from the high-density nursery plots. Family, density, and family × density effects all significantly influenced root volume of 1–0 stock at lifting (Table 3). In 2004, after the first growing season at SEPAC, gld of seedlings from low density nursery plots was significantly larger than seedlings from the medium density and high density treatments (Table 2). The height of the seedlings from the low density nursery treatment was significantly greater than the other two treatments in 2004, in contrast with the result from the previous year.

Correlations among traits within and between years

At lifting, the correlations among seedling growth traits in 2003 were strongly density-dependent. The strongest correlation was between root volume and height at low density ($r = 0.76$, $P < 0.0001$), but the correlation between root volume and height decreased to 0.47 at medium density, and to 0.34 at high density. Surprisingly, the opposite trend was observed for correlations among the other traits. At lifting, ground line diameter was more strongly correlated with height ($r = 0.6$) and root volume ($r = 0.58$) for seedlings grown at high density than for seedlings grown at medium ($r = 0.22$, 0.21) and low density ($r = 0.28$, 0.22). All correlations among growth traits in 2003 were highly significant

Table 3 Analysis of variance for growth traits of black walnut seedlings from nine open-pollinated half-sib families grown at three densities in the nursery

Year	Trait[a]	Effect	DF (Num)	DF (Den)[b]	F	Pr > F
2003	Root volume	Density	2	6.39	19.9	0.002
		Family	10	77.1	11.6	<0.001
		Density × Family	20	77.3	2.89	<0.001
2004	Height	Density	2	14	3.89	0.045
		Family	8	166	6.73	<0.001
		Density × Family	16	166	1.01	0.444
	GLD	Density	2	14.1	8.40	0.004
		Family	8	166	6.99	<0.001
		Density × Family	16	166	0.67	0.822
2009	Height	Density	2	14.1	2.41	0.125
		Family	8	166	3.06	0.003
		Density × Family	16	166	1.06	0.393
	GLD	Density	2	14	4.53	0.030
		Family	8	166	4.38	<0.001
		Density × Family	16	166	0.84	0.644
	DBH	Density	2	179	4.80	0.009
		Family	8	179	2.99	0.004
		Density × Family	16	179	0.86	0.615

Traits were measured after lifting (root volume) or after the first and fifth growing season in a plantation (height, ground-line diameter, dbh)

[a] GLD = Ground line diameter, DBH = Diameter at 1.5 m

[b] Denominator degrees of freedom (DF) = error DF for each test

($P < 0.001$). Family ranks in 2003 were not significantly correlated with family ranks in 2009 for any variables.

In 2009, all the observed growth variables were highly correlated ($0.8 < r < 0.9$), and all the correlations were very highly significant (Table 4). The (Pearson) correlations among traits were only weakly sensitive to planting density, although in general seedlings from the low density treatment had slightly higher correlations with other traits than seedlings grown in medium or high density plots. A similar pattern was observed in the data in 2004, when the correlation between seedling height and diameter was consistent and extremely high ($0.89 < r < 0.91$) for each of the three density treatments. Correlations between seedling size after 2004 and size 5 years later were also high and highly significant (Table 4). As the density of the seedlings in the nursery increased, the magnitude of the correlations between 2004 and 2009 decreased.

Growth after 5 years

In 2009, after the fifth growing season, survival was 97%. Seedlings from the low density nursery plots were about 11–13 cm taller than the seedlings from the same families grown in medium or high density nursery plots, a small and non-significant difference (Table 2). It is worth noting that the slight height advantage that the high density seedlings showed in 2004 over the medium density treated seedlings was retained for 5 years. In 2009, the

Table 4 Pearson correlations among measured traits in 2004 and 2009. Correlations for each nursery density treatment are in parentheses

Trait (*Density*)[a]	Ground line diameter 2004	Height 2009	Ground line diameter 2009	DBH 2009
Height 2004	0.902	0.73	0.75	0.70
(*L, M, H*)	(*0.90, 0.91, 0.89*)	(*0.76, 0.71, 0.69*)	(*0.79, 0.75, 0.67*)	(*0.72, 0.71, 0.67*)
GLD 2004		0.67	0.81	0.65
(*L, M, H*)		(*0.70, 0.66, 0.63*)	(*0.84, 0.81, 0.75*)	(*0.65, 0.66, 0.63*)
Height 2009			0.84	0.88
(*L, M, H*)			(*0.86, 0.85, 0.82*)	(*0.89, 0.87, 0.88*)
GLD 2009				0.83
(*L, M, H*)				(*0.83, 0.83, 0.81*)

All correlations were very highly significant, $P \leq 0.0001$, $n \geq 250$

[a] Density treatments included Low (11.2 seeds m^{-2}), Medium (24.2 m^{-2}), and High (29.4 m^{-2})

diameter (dbh) and ground line diameter (gld) of the seedlings from the low density nursery plots were significantly larger than those from the other two treatments. The gld of the seedlings increased about 80% between 2004 and 2009, from 25.0 to 47.0 mm, across all density treatments. The change in gld from 2004 to 2009 was nearly equal for the seedlings irrespective of nursery density treatment, i.e., 22.7 mm for seedlings from low density nursery plots, 21.9 mm from high density nursery plots, and 21.4 from medium density nursery plots (Table 2).

Family and density effects on black walnut seedling growth

Family effects were considerably more important than nursery density effects in determining the size of seedlings in 2004 and 2009 (Tables 3, 5). An analysis of the variance components showed that family was responsible for about 18% of the total variance for both height and gld in 2004, considerably more than the variance due to nursery sowing density (Table 5). Interaction effects were small. The results were similar in 2009, except treatment effects (both family and density) in 2009 accounted for a lower percentage of the total variance than in 2004. In 2004, the variance for family effects was greatest among seedlings grown at medium density, for both height and gld (Table 5), although the mean height and diameter of seedlings from the medium density plots were not significantly different than the high density plots. In 2009, family accounted for 26% of the total variance in gld of trees grown at medium density in the nursery, but family had no measurable effect on the gld of trees grown at low density. In 2009, the range of family means (Table 2) for height and dbh was greatest for seedlings sown at low density in the nursery, but for gld, the medium density treatment produced the greatest range of family means.

None of the families was significantly larger than any other for any of the traits, irrespective of density, but in 2009 we observed large differences among families' means that were not the result of family × density interactions (there were significant interaction effects in 2004). For example, five families' seedlings grown at high density had mean heights in 2009 that were greater than the shortest family's seedlings grown at low density (data not shown, but see Table 2). Similarly, two families' seedlings grown at high density had larger dbh than the smallest dbh family grown at low density, and five families grown at high density had a larger gld than the smallest gld family grown at low density. A similar result was observed in 2004 (Jacobs et al. 2005a, b). Family rank for growth was not highly

Table 5 Proportion of total phenotypic variance for seedling traits attributed to each source in 2004 and 2009, and the effect of nursery bed density on the proportion of total phenotypic variance for each measured trait due to half-sib family

Source (*Density*)	2004 traits		2009 traits		
	Height (%)	Diameter (%)	Height (%)	Diameter (%)	Ground-line diameter (%)
Family (*L, M, H*)	18.6 (*1.8, 29,15.3*)	17.8 (*4.6, 19.3, 8.8*)	7.1 (*0.0, 8.6, 10.5*)	7.4 (*1.7, 9.0, 5.5*)	11.1 (*0.0, 26.2, 12.3*)
Block × Family	0	0	2.5	1.3	4.0
Density	3.2	10.3	2.1	5.0	6.3
Family × Density	0.2	0	0.9	0	0
Block × Density	0.4	3.4	2.1	0	5.1
Error	78	68.6	85	86.5	73

[a] Density treatments included Low (11.2 seeds m^{-2}), Medium (24.2 m^{-2}), and High (29.4 m^{-2})

consistent from 2004 to 2009. Family rank correlations (Spearman) for variables measured in different years were generally not significant, except family rank for both height and diameter in 2004 were highly correlated with family rank for gld in 2009 ($r = 0.75$ and 0.76, respectively), and the correlations were significant (alpha ≤ 0.05 in both cases).

Family and density effects on seedling quality

In 2009, seedlings were rated for quality using a 1–5 scale, and for the presence/absence of a central terminal. Density treatment had no effect on seedling quality (χ^2 10 $df = 7.28$, $P = 0.696$) or presence/absence of a central terminal (χ^2 2 $df = 3.19$, $P = 0.203$). Families differed significantly with respect to presence of a terminal (χ^2 8 $df = 18.1$, $P = 0.02$); about 61% of the trees of the best family (based on quality ratings) had a central terminal, the worst family had 38%, while the plantation average was about 55%. When quality categories were pooled, however, so that all below-average trees were in a single category (category 1, 2 = "unacceptable"), and all above-average trees were in another category (category 4, 5 = "acceptable"), we observed a significant family effect on quality, but not a density effect on quality (χ^2 8 $df = 22.1$, $P = 0.0046$; χ^2 2 $df = 0.455$, $P = 0.79$).

Response to increased bed space

Two families from improved parents contained the largest seedlings in 2009, and the same families also had the greatest response to reduced nursery density, as measured by the percent increase in height (18%) and gld (21.5%) when grown at low density versus high density. The average response (low versus high density) for all families was 13.5% for height and 11.5% for gld. The same two families ranked second and fifth for both height and ground line diameter after the first year of growth.

Discussion

Although the influence of genetic source in plantation growth of black walnut trees has been well documented (Beineke 1989), the genetics of walnut nursery stock quality is not well researched. Studies of other species within Juglandaceae generally revealed significant family variation among seed sources. For instance, Dixon (1988) reported significant variation in black walnut seedling shoot and root growth among three seed sources collected in Minnesota, USA that were inoculated with different strains of mycorrhizal fungi. McGranahan et al. (1988) reported that seed source was a highly significant cause of variation for phenological traits and branching in California black walnut (*Juglans hindsii* Jeps. ex R.E. Smith) seedlings. Furthermore, significant variation in seedling growth was found among nine full-sib pecan (*Carya illinoinensis* (Wangenh.) C. Koch) sources (Thompson and Grauke 2003), and the authors suggested that nurseries could improve pecan rootstock vigor by planting seeds of selected families.

Previous research showed that larger black walnut seedlings were produced at lower seedbed densities (Schultz and Thompson 1996). Our results confirm these findings, along with reinforcing the importance of genetics in determining seedling size and tree form. Schultz and Thompson (1996) reported that all morphological variables, including shoot height, increased at lower sowing densities, although their study included much higher seedbed densities than did ours (i.e., 32–96 vs. 11–29 seedlings m^{-2}). Although nursery sowing density had a significant effect on seedling height in our study in 2004, and although shoot height is one of the more obvious indicators of seedling vigor, shoot height can be an inconsistent predictor of field performance (Chavasse 1977; Thompson and Schultz 1995), and we contend that root morphology and gld better reflect nursery stock quality. Nursery density remained a significant factor determining dbh and gld in 2009, but not tree height. Overall, however, family was a more significant factor in determining seedling growth after 5 years than was nursery density (Tables 3, 5). This indicates that the current system of optimizing tree growth by adjusting planting density may be less effective than planting seeds from the best families. The use of seed from selected parents could improve the quality of seedlings at the current planting density. Alternatively, by planting families that have been proven to perform well when grown at high nursery-bed densities, seedling quality could be maintained even at higher planting densities.

Family variance was greatest for height and gld at moderate planting densities, both in 2004 and 2009, although the differences among sowing densities in revealing family effects were most pronounced at the earlier time. These findings indicate that evaluation and selection of families for size at lifting should take place at moderate sowing densities, and that the use of moderate sowing densities in the nursery would also be suitable for later genetic trials. Our observation that the effect of family on the variance of some traits was negligible after 5 years for some nursery densities may also explain why the efficiency of early selection in black walnut has been controversial (Aletà et al. 2004). The relationship between the timing of onset of competition and the expression of family differences in growth is an important but poorly understood area of research in hardwoods. It has been observed that the heritability of height for black walnut is very high in the first couple years of growth but decreases considerably thereafter (Rink 1984). In conifers, the data indicate that competition generally increases growth differences among families, and improved germplasm typically is more responsive to enhanced cultural conditions than unimproved sources (Namkoong and Conkle 1976). The genetics of competition among trees in the nursery has not been much researched, but St. Clair and Adams (1991) concluded that family and competition effects were much larger than family × competitive environment interactions.

We observed that Pearson correlations among traits within years were positive, high to very high in magnitude, and highly significant (Table 4). The correlations among the traits were not much affected by planting density. This result, taken together with those reported above, may indicate that a single measurement (e.g., gld) may be adequate to identify families that produce superior quality nursery stock, and may even be sufficient for preliminary family selection (or the removal of certain families as seed sources) as long as seedlings were grown at an appropriate density and variability caused by differences in emergence time is removed. The physiological mechanisms by which nursery bed density influences variance among families for growth remains an important research question.

The factors that affect tree growth in the early years after planting are critical because it is important to produce hardwood seedlings that are free to grow as quickly as possible. Competing vegetation and herbivory can degrade (Zaczek et al. 1996) or even destroy the long term potential of a plantation. Whether the statistical differences we observed among nursery treatments at age five will result in important biological or economic differences at harvest remains to be determined.

Conclusions

These results reinforce the importance of nursery sowing density in producing high quality black walnut nursery stock for seedling production. We found, however, that half-sib seed source was relatively more important than sowing density in determining seedling shoot and root morphological quality. This indicates that the common practice in the Central Hardwood Region of obtaining seed from sources of unknown genetic origin limits the production of high quality nursery stock. In addition, if these results prove consistent over a wider range of studies, managers who use improved seed sources for nursery stock may need to re-evaluate their standard sowing density because it may be possible to improve production volume or quality without increasing nursery bed space. Selection of superior genetic sources could enhance stock quality, much as irrigation, fertilization, weed control, and root culturing practices have increased nursery yields and improved plantation success (Jacobs 2003). Our study was limited to a single nursery and a single year. A test of a wide array of genetic sources screened over several nursery locations, years, and plantation management scenarios would be needed to generalize the results we observed (South et al. 2001).

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