

Natural variation and genetic parameters in Fraser fir for growth and Christmas tree traits

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Open-pollinated progeny trials of Fraser fir (*Abies fraseri* (Pursh) Poir.) assessed at 8 years provided genetic parameter estimates for growth, Christmas tree quality traits, and wholesale value at harvest age. Significant variation was found between and within nine different seed sources. Estimated individual tree heritabilities of important traits ranged from a low of 0.13 for USDA Christmas tree grade to a moderate value of 0.33 for crown diameter. Heritabilities within the better performing seed sources tended to be higher. Of the two traits that determine wholesale value, USDA grade and height class, the latter proved to have the greater influence, both phenotypically and genetically. Genetic correlations of early age height growth with 8-year total height, height class, USDA Christmas tree grade, and individual tree wholesale value proved favorable and strong (range of 0.57–0.96). In combination with moderate heritabilities for early growth traits, such correlations provide potential for effective early age selections in Fraser fir Christmas trees.

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Des tests de descendance issues de pollinisation libre du sapin de Fraser (*Abies fraseri* (Pursh) Poir.) ont été évalués à 8 ans et ont permis d'obtenir des estimés de paramètres génétiques pour la croissance, des caractères de qualité d'arbre de Noël et la valeur de vente en gros à l'âge de la récolte. Les estimés d'héritabilité au sens strict des caractères importants variaient d'un minimum de 0,13 pour la classe d'arbre de Noël déterminée par le USDA, jusqu'à une valeur modérée de 0,33 pour le diamètre de la cime. Les héritabilités évaluées à partir des sources de graines les plus performantes affichaient généralement des valeurs plus élevées. Entre les deux caractères déterminant la valeur de vente en gros, c'est-à-dire la classe USDA et la classe de hauteur, le second a démontré une plus grande influence, à la fois phénotypiquement et génétiquement. Les corrélations génétiques furent estimées entre la croissance précoce en hauteur et les caractères à l'âge de 8 ans, à savoir la hauteur totale, la classe de hauteur, la classe d'arbre de Noël du USDA et la valeur de vente en gros des arbres individuels. Ces corrélations étaient favorables et fortes (étendue de 0,58 à 0,96). En combinaison avec les héritabilités modérées observées pour les caractères de croissance précoce, de telles corrélations permettraient une sélection précoce efficace pour les arbres de Noël chez le sapin de Fraser.

[Traduit par la rédaction]

Introduction

Fraser fir (*Abies fraseri* (Pursh) Poir.) is a small- to medium-size tree of up to 25 m in height in natural stands. Its natural range is limited to small disjunct populations found on mountain ridges above 1200 m in western North Carolina, southern Virginia, and eastern Tennessee (Radford et al. 1968; Pittillo 1984). This species is closely related to balsam fir (*Abies balsamea* (L.) Mill.), whose native range is more extensive and to the north of Fraser fir's.

Over the past 30 years, Fraser fir has gained substantial economic importance as a fresh cut Christmas tree. It is now widely recognized as the premier species for this application in the United States and commands appropriately high prices (Cook 1990). Excellent natural shape, pleasant aroma, strong branches, dark blue-green foliage, and superior post-harvest needle retention are among its desirable attributes.

The Fraser fir Christmas tree industry, despite its economic magnitude and importance, has relied on unimproved and largely unselected seed sources. Little investment has been made in selection and genetic improvement of the species. Great demand for seed from growers has pushed collections to the most accessible natural sources as determined by seed productivity and ease of cone harvesting.

Little consideration has been given to relative performance of either different mountain sources, or individual seed parents within mountain sources.

To date, no rotation age (8-year) estimates of genetic variation or of genetic parameters have been reported for Fraser fir. In fact, there are no published estimates of genetic parameters for sheared, go to market Christmas trees of any species. Such information would serve two immediate needs. First, quantification of variation and relative performance of sources will enable growers to immediately focus seed collections on superior natural sources. Second, knowledge of the patterns of such variation in combination with quantification of genetic parameters is essential for breeders to formulate efficient breeding strategies and predict gains for an intensively managed high unit value product.

Limited estimates of genetic variation in Christmas tree growth and quality traits have been obtained for a few commercially important species. Progeny test selection of the best 10% of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) parents was found to yield an 18% gain in average tree value (Silen and Wilson 1977). In balsam fir, both provenance and family within provenance selection have been found important to maximize genetic gains for Christmas tree growth and quality traits (DeHayes et al. 1982). Significant seed source variation in Christmas tree growth and quality, along with moderate to strong heritabilities of these

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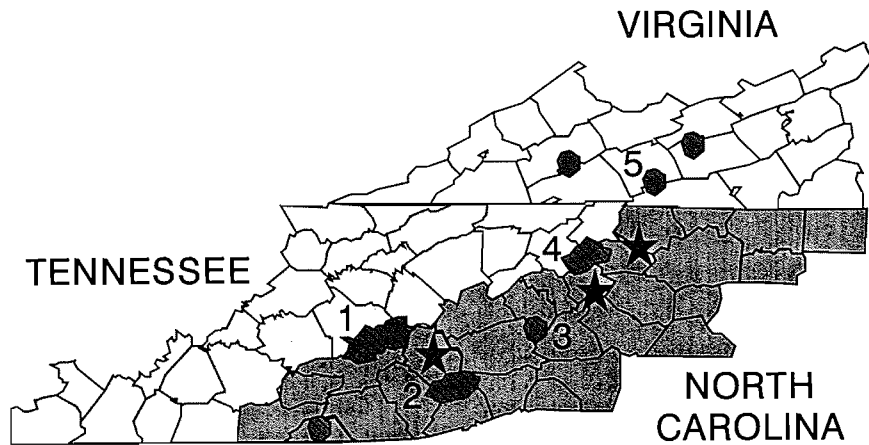


FIG. 1. Location of Fraser fir seed sources (indicated by the numbers), natural populations (indicated by diagonally striped areas), and the seed source trials (indicated by star symbols). Seed source No 1 is Clingman's Dome, 2 is Richland Balsam, 3 is Mount Mitchell, 4 is Roan Mountain, and 5 is Mount Rogers.

at age 3 years, have also been found in Virginia pine (*Pinus virginiana* Mill.) (Warlick et al. 1985). More recently, one study with Virginia pine estimated that substantial increases in height growth and quality would be obtainable with clonal selection and propagation (Brown and Foster 1991).

In 1983, the first genetic field tests of Fraser fir were established in western North Carolina by the Department of Forestry at North Carolina State University. Preliminary analyses of data from these tests at ages 1 and 4 years indicated important genetic variability within this species for both growth and form traits (Li et al. 1988; Jett et al. 1993).

The objectives of the current study were twofold: (i) to examine levels of genetic variation within the natural Fraser fir populations for growth and Christmas tree quality traits, as revealed in the 8-year (rotation age) assessment of the 1983 North Carolina Fraser fir trials; and (ii) to estimate genetic parameters for such traits. The results of seed source differences are presented elsewhere (Arnold 1993).

Materials and methods

Sampling

Open-pollinated seeds were originally obtained from over 90 parent trees throughout Fraser fir's natural range. Ten parent trees were sampled from each of nine separate seed sources drawn from five of the disjoint mountain populations (Li et al. 1988; Jett et al. 1993) (Fig. 1). Subsequent poor seed germination, seedling survival, and establishment reduced the number of families represented in the field tests to 82. Similarly, the number of families for some seed sources was reduced to as low as six.

Propagation and field tests

Seeds were sown in 1980 and grown initially in a greenhouse. After 1 year the seedlings were transplanted to open beds at the N.C. Division of Forestry Nursery at Crossnore, N.C., for an additional two seasons' growth prior to establishment in field tests. A randomized complete block design was used in both the greenhouse and nursery with six replications and five seedlings per family plot.

Field trials were established at three locations in western North Carolina in 1983. A randomized complete block field design was employed, with five trees per family randomly positioned in each of six blocks (i.e., noncontiguous plots) at each site. Trees were planted at a 1.83 × 1.83 m spacing. Complete details of the propagation and field testing have been presented previously by Li (1985), Li et al. (1988), and Jett et al. (1993).

Culture

Intensive weed control measures were practiced at all three field sites. Also, all trees were shaped and sheared annually after the fourth growing season. Such cultural practices are considered routine and essential to produce quality Fraser fir Christmas trees that both appeal to consumers and satisfy USDA marketing standards.

Measurement

Each tree was measured at four separate ages. At planting in 1983 (field age 0 years, tree age 3 years), heights were measured. After 1 year in the field, height and number of terminal buds were assessed for each tree. In 1987, after 4 years in the field, each tree was assessed for height, maximum crown diameter, and branch diameter of the longest branch in the topmost whorl. Finally after 8 growing seasons in the field in 1991 (tree age 11 years), all trees were measured for: (i) total height; (ii) crown diameter, maximum crown width taken in two perpendicular directions and then averaged; (iii) branch diameter, the diameter just beyond the point of basal swelling of the longest branch in the topmost whorl; (iv) density of the crown, scored on a subjective scale of 1 (heavy) to 3 (light) in accordance with USDA grading standards (U.S. Department of Agriculture 1989); (v) straightness, also scored subjectively on a scale of 1 (straight) to 3 (crooked) in accordance with USDA Christmas tree-grading standards. In addition, following year-8 shaping and shearing, each tree was scored for USDA grade and for merchandizing height class. The grades in decreasing quality order are premium, No. 1, No. 2, and cull, as defined by the USDA standards (U.S. Department of Agriculture 1989). Merchandizing height class is the total post-shearing height less a 76 mm stump, rounded down to the nearest trading height category.² Those in typical use at present (in whole foot increments starting at 4 ft.), as adopted in this study, were 4.0–4.9 ft. (1.22–1.49 m), height class 4–5; 5.0–5.9 ft. (1.52–1.80 m), height class 5–6; 6.0–6.9 ft. (2.13–2.41 m), height class 7–8; 8.0–8.9 ft. (2.44–2.71 m), height class 8–9; and 9.0–9.9 ft. (2.74–3.02 m), height class 9–10. Taken together, the grade and height-class measures directly enabled a wholesale value to be determined for each tree based on the actual 1991 industry values reported by Arnold (1993). For qualitative analyses in this study, USDA grades were assigned numerical values as follows: premium = 0; No. 1 = 1; No. 2 = 2; and cull = 3.

²These classes are shown in Imperial "feet" units, as they are the industry standard. Converting them to metric renders them meaningless for people in the Christmas tree industry. The class units are basically the same as discrete names and not units of measurement per se.

TABLE 1. ANOVA mean squares for growth and Christmas tree form traits in Fraser fir at age 8 years, computed on family-plot means

Source	df	Total height	Crown diameter	Branch diameter	Straightness	Density	USDA grade	Wholesale value	Height class
Site	2	49.900**	78.8000**	0.057 89**	4.900**	51.700**	38.300*	4119.700**	125.935**
Replication (Site)	14	2.600**	3.8000**	0.001 68**	2.700**	2.800**	1.700**	64.700**	1.591**
Seed source	8	4.771**	3.2510**	0.002 25**	0.403**	1.820**	1.040**	88.141**	3.470**
Site × seed source	16	0.553**	0.2930**	0.002 92*	0.209*	0.130ns	0.151ns	10.037**	0.385**
Replication × seed source	112	0.207ns	0.0869ns	0.000 47ns	0.141*	0.090ns	0.119ns	4.076ns	1.090ns
Family (seed source)	73	1.108**	0.5574**	0.001 32**	0.496**	0.501**	0.438**	23.423**	0.780**
Site × family (seed source)	120	0.215ns	0.0874ns	0.000 54ns	0.110ns	0.115*	0.160**	5.539ns	0.178ns
Error	911	0.202	0.0829	0.000 376 55	0.112	0.086	0.116	4.553	0.167

*, **, Mean square significant at the 0.05 and 0.01 level, respectively; ns, not significant at $p \leq 0.05$.

Analyses

For evaluating the magnitude and significance of family variation, and family × site interaction effects, analyses of variance were computed on family plot means. The model for these analyses incorporated the following effects: sites; blocks (within sites); seed source; site × seed source interaction; blocks (within sites) × seed source; family (within seed source); site × family (within seed source); and error (family by block mean). All effects were assumed random except for seed source. As the sources were intentionally chosen and would remain equivalent if the trials were to be repeated, seed source was treated as fixed effect. The general linear model (GLM) procedure of the Statistical Analysis System (SAS Institute Inc: 1985) provided appropriate sums of squares (type IV).

A separate analysis of variance on individual tree data was used for estimation of variance components. For this, the preceding model was expanded to include an error component that represented individual trees (within family × block). Again, all effects were assumed random except for seed source. Variance and covariance component estimates were obtained using type IV sums of squares in PROC VARCOMP of the Statistical Analysis System (SAS Institute Inc. 1985).

Genetic parameters

Heritabilities, standard deviations of these heritabilities, genetic correlations, standard deviations of these correlations, and phenotypic correlations were estimated according to Falconer (1989).

In the estimation of individual heritability, it was assumed that progeny from any one of the parent trees sampled were true half-sibs, and therefore have a coefficient of relationship of 0.25 (Falconer 1989). The validity of this assumption is unknown for open-pollinated progeny from natural Fraser fir stands. If some proportion of the progeny were produced through self-pollination or matings among relatives, using 4 as the multiplier for family variance would inflate the heritability estimates (Namkoong 1966; Squillace 1974). However, the coefficient of 4 was used, as it provides a common basis for comparison with other studies, and in the absence of known ancestral relationships there is no basis to adopt a different coefficient value.

Results and discussion

Significant differences ($p < 0.01$) were found among seed sources and among families within seed sources, for all traits assessed (Table 1). The range in seed source mean heights from 2.19 to 2.36 m, and in wholesale values from \$15.74 to \$18.06 emphasizes the importance of seed source selection in Fraser fir (Table 2). The value of subsequent selection at the family within seed source level is indicated by the significance of family effects (Table 1). Within the best seed source for height growth at 8 years, Richland Balsam 1500 m, family mean wholesale values ranged from 91.5 to 111.2% of that source's mean. In the poorest source, Mount Mitchell 1950 m, they ranged from 82.3 to 110.6%. Variation of a similar magnitude has been reported in the growth of balsam fir Christmas trees (DeHayes et al. 1982).

Results of earlier isozyme studies showed apparent low genetic diversity within the Mount Rogers seed source, in comparison with other seed sources of Fraser fir (Diebel 1989; Ross 1988). However, results here show that phenotypic variation between families within Mount Rogers was equal to or greater than that within other seed sources. Family means as a percentage of the seed source mean from Mount Rogers ranged from 92.1 to 106.6% for 8-year total height, and from 87.3 to 111.45% for wholesale value.

Crown density and USDA grade showed significant but small site × family interaction (Table 1). This interaction accounted for only 1.5 and 2.1% of the total phenotypic

TABLE 2. Means and individual tree heritabilities (with standard deviations given in parentheses) by seed source for Fraser fir growth and Christmas tree form traits at age 8 years

Seed source	Elevation (m)	No. of families	Total height(m)		Crown diameter(m)		USDA grade ^a		Wholesale value (\$)	
			\bar{x}	h_i^2	\bar{x}	h_i^2	\bar{x}	h_i^2	\bar{x}	h_i^2
Clingman's Dome	1500	10	2.32	0.65 (0.19)	1.24	0.73 (0.20)	0.74	0.32 (0.13)	17.55	0.58 (0.18)
Clingman's Dome	1650	6	2.32	0.26 (0.15)	1.26	0.27 (0.15)	0.65	0.14 (0.11)	17.79	0.28 (0.16)
Clingman's Dome	1800	10	2.20	0.14 (0.09)	1.14	0.12 (0.09)	0.89	0.16 (0.10)	15.74	0.07 (0.06)
Richland Balsam	1650	9	2.36	0.24 (0.12)	1.26	0.10 (0.08)	0.67	0.04 (0.05)	18.06	0.19 (0.11)
Roan Mountain	1650	10	2.27	0.13 (0.07)	1.16	0.42 (0.14)	0.68	0.05 (0.05)	17.10	0.01 (0.02)
Roan Mountain	1800	10	2.22	0.15 (0.08)	1.16	0.22 (0.10)	0.68	0.17 (0.09)	16.78	0.17 (0.09)
Mount Mitchell	1800	8	2.29	0.06 (0.06)	1.19	0.01 (0.02)	0.76	0.05 (0.05)	17.09	0.03 (0.04)
Mount Mitchell	1950	9	2.19	0.42 (0.14)	1.13	0.44 (0.14)	0.80	0.16 (0.05)	15.73	0.26 (0.11)
Mount Rogers	1500	10	2.30	0.39 (0.15)	1.18	0.47 (0.17)	0.75	0.15 (0.06)	16.79	0.31 (0.13)

^aUSDA class has been represented here as a numerical value: premium = 0; No. 1 = 1; No. 2 = 2; cull = 3.

TABLE 3. Means and heritabilities for Fraser fir growth and Christmas tree form traits at age 8 years

Trait	Mean	Phenotypic variance	Individual heritability	Family heritability
Total height (m)	2.27	0.09	0.26 (0.040)	0.69 (0.064)
Crown diameter (m)	1.18	0.05	0.33 (0.044)	0.75 (0.067)
Branch diameter (mm)	7.67	1.60	0.08 (0.022)	0.41 (0.050)
Density (score)	1.92	0.41	0.25 (0.040)	0.67 (0.065)
Straightness (score)	1.60	0.47	0.22 (0.037)	0.66 (0.064)
USDA grade (score)	0.72	0.48	0.12 (0.027)	0.46 (0.054)
Wholesale value (\$)	16.94	18.49	0.21 (0.036)	0.63 (0.063)
Height class	1.98	0.06	0.23 (0.038)	0.66 (0.065)

NOTE: Standard deviations of heritability estimates are given in parentheses of Fraser fir growth and form traits with age.

variance in density and USDA grade respectively. Such effects will be of little concern to breeders over the range represented by the random sample of sites involved in this study.

Heritabilities

Individual heritabilities were low to intermediate (i.e., $0.10 \leq h_i^2 \leq 0.30$) for all but two of the traits assessed at age 8 (Table 3). Crown diameter ($h_i^2 = 0.33 \pm 0.04$; mean \pm SD) proved to be the most highly heritable of all the traits while branch diameter had the lowest heritability ($h_i^2 = 0.08 \pm 0.02$). Heritabilities for all traits were estimated with high precision, largely a consequence of the large numbers of trees in this study.

USDA grade proved to have the second lowest heritability of traits assessed ($h_i^2 = 0.12 \pm 0.03$). Together USDA grade and 8-year height class determine wholesale value. However, individual heritability for wholesale value ($h_i^2 = 0.21 \pm 0.04$) is much closer to that of 8-year height class ($h_i^2 = 0.23 \pm 0.04$) which itself is nearly double that for USDA grade. This is indicative of the overwhelming importance of height in the determination of Fraser fir Christmas tree value. The dominance of height over quality traits in value determination has also been found in other Christmas tree species (Silen and Wilson 1977; Warlick et al. 1985). Height, consequently, will tend to be the single most profitable trait by which to obtain indirect improvement of Fraser fir Christmas tree value.

The estimates of individual 8-year heritabilities obtained for Fraser fir are very encouraging for tree breeders. Genetic

TABLE 4. Change in heritabilities of Fraser fir growth and form traits with age

Trait	Age (years)	Individual heritability	V_a/V_c (%)
Total height	0	0.15	20.4
	1	0.25	36.5
	4	0.41	68.1
	8	0.27	36.1
Crown diameter	4	0.33	49.9
	8	0.33	50.0
Branch diameter	4	0.28	38.4
	8	0.08	8.7
No. of terminal buds	1	0.14	15.9
	4	0.14	16.2

NOTE: V_a represents the additive genetic variance, and V_c represents the phenotypic variance of individuals less the family variance.

control of all traits, except branch diameter, is sufficiently strong so each should respond well to selection and breeding.

Family heritabilities for all traits were substantially greater than individual values (Table 3). As with individual heritabilities, crown diameter had the greatest family heritability ($h_i^2 = 0.75 \pm 0.07$), and branch diameter the lowest ($h_i^2 = 0.41 \pm 0.05$). Family performance of Fraser fir clearly provides a superior guide to the breeding value of any individual. Substantial response to family selection in Fraser fir should be obtainable for any one of the traits studied.

Age-4 heritability estimates from this study, reported previously by Liu (1991), as well the age-8 estimates presented

TABLE 5. Genetic (r_a) and phenotypic (r_p)

	Branch diameter		Density		Straightness	
	r_a	r_p	r_a	r_p	r_a	r_p
Crown diameter	0.23 (0.13)	0.13**	-0.52 (0.07)	-0.42**	0.51 (0.08)	0.09**
Branch diameter			-0.07 (0.14)	0.02ns	-0.43 (0.12)	0.06ns
Density					0.10 (0.11)	0.09**
Straightness						
USDA grade						
Wholesale value						

NOTE: Standard deviations of the genotypic estimates are given in parentheses.

*, **: phenotypic correlation significant at the 0.05 and 0.01 level respectively; ns, not significant.

here for Fraser fir Christmas trees exceed those reported for equivalent traits in unshaded 3-year Virginia pine ($h_i^2 = 0.16$; Warlick et al. 1985). Also for comparison, Beaulieu et al. (1990) reported total height individual heritabilities for unshaded trees of the closely related balsam fir of 0.28 ± 0.12 and 0.19 ± 0.09 for 5 and 10 years respectively, which were similar to that for Fraser fir at 8 years. However, the heritability for 8-year Fraser fir straightness ($h_i^2 = 0.22 \pm 0.04$) substantially exceeded that for 10-year balsam fir ($h_i^2 = 0.08 \pm 0.05$).

Heritabilities within seed sources

One concern in estimating heritabilities with material from a range of seed sources, as in this study, is that the values represent averages across sources. Inaccurate gain estimates for selection and breeding strategies can result if genetic control of important traits within selected sources differs substantially among sources.

Individual heritabilities within seed sources for 8-year total height, crown diameter, and USDA grade varied from weak to strong ($h_i^2 = 0.01 \pm 0.02$ to 0.73 ± 0.20 ; Table 2) indicating large differences in the genetic control of traits exists within different sources of Fraser fir. However, the three top-performing seed sources (Richland Balsam 1650 m; Clingman's Dome 1650 m; and Clingman's Dome 1500 m (Arnold 1993)) had moderate to strong genetic control of total height ($h_i^2 = 0.24 \pm 0.12$ to 0.65 ± 0.19) and wholesale value ($h_i^2 = 0.19 \pm 0.11$ to 0.58 ± 0.18), and tended to exceed the overall average heritabilities for each of these traits.

The utility of these within-source heritability estimates is limited by their large standard errors. The magnitudes of these errors were due largely to the limited number of families representing each source. However, the heritability estimates obtained do provide valuable information for tree breeders. They clearly indicate that significant and usable variation does exist within each of the better Fraser fir seed sources.

Changes in heritabilities with age

Individual heritability for total height increased from both field ages 0 to 1, and 1-4 years, but then decreased substantially from 4 to 8 years (Table 4). The marked decrease in the later period is associated with a proportionately larger decrease in the genetic than in the phenotypic coefficient of variation, and likely arose owing to the use of specific cultural treatments. Annual shearing and shaping of trees, including topping of leaders to encourage denser form, commenced after the 4-year assessment. Such treatment reduces the height variation between individuals. Consequently, genetic expression of total height growth potential is partially

masked by the standard Christmas tree silviculture, which tends to increase height uniformity.

Shearing and shaping are required to set a good conical Christmas tree form with even taper that appeals to consumers. Lower crown branch whorls largely set this form and this portion of the crown is little impacted by shearing. This may in part or even wholly account for the consistency of additive genetic control of crown diameter from 4 to 8 years.

Heritability of branch diameter, in contrast to that of crown diameter, declined substantially from 4 to 8 years. Development of the better form by shearing typically necessitates severe reduction in length of the uppermost branch whorls, which severely reduces branch diameter growth in those whorls and partially masks expression of individual genetic potential.

Correlations

Interpretation of correlation estimates for density, straightness, and USDA grade necessitates awareness that lower scores for each of these traits are in fact superior. The estimates of the genetic correlations obtained tended to be relatively imprecise as indicated by their standard deviations (Tables 5 and 6). Correlations, both phenotypic and genetic, proved to be strong and favorable among growth traits in this study. Favorable, moderate correlations between total height and other important Christmas tree traits has also been found in Virginia pine (Warlick et al. 1985). One exception to this is between Fraser fir crown diameter and branch diameter, which had only a moderate genetic correlation ($r_a = 0.23 \pm 0.13$) and a low phenotypic correlation ($r_p = 0.13$). As discussed above, cultural practices that affected expression of branch diameter may also have affected both of these correlations. The strongest correlation proved to be for height class with wholesale value ($r_a = 0.97 \pm 0.01$, $r_p = 0.89$).

The only unfavorable genetic correlation exposed in this study was between USDA grade and branch diameter ($r_a = 0.38 \pm 0.15$). However, the imprecision of this estimate and the very low phenotypic correlations of branch diameter with USDA grade ($r_p = -0.02$) and wholesale value ($r_p = 0.09$) make this unfavorable correlation inconsequential.

Wholesale value showed very strong genetic and phenotypic correlations with the two traits that determine it: 8-year height class ($r_a = 0.97 \pm 0.01$, $r_p = 0.89$) and USDA grade ($r_a = -0.79 \pm 0.05$, $r_p = -0.73$) (Table 5). Crown diameter and density also showed strong favorable correlations with wholesale value.

Of greater significance, though, is the moderate favorable correlation between height class and USDA grade

correlations between 8-year Fraser fir traits

USDA grade		Wholesale value		Total height		Height class	
r_a	r_p	r_a	r_p	r_a	r_p	r_a	r_p
-0.32 (0.11)	-0.37**	0.78 (0.04)	0.65**	0.93 (0.01)	0.71**	0.87 (0.03)	0.70**
0.38 (0.15)	-0.02*	0.57 (0.11)	0.10**	1.16 (0.05)	0.30**	0.35 (0.13)	0.14**
0.90 (0.02)	0.52**	-0.79 (0.05)	-0.47**	-0.48 (0.08)	-0.31**	-0.64 (0.03)	-0.34**
0.36 (0.12)	0.12**	-0.23 (0.12)	-0.07**	-0.39 (0.01)	0.06**	-0.42 (0.01)	0.02**
		-0.79 (0.05)	-0.73**	-0.45 (0.10)	-0.33**	-0.61 (0.08)	-0.35**
				0.90 (0.02)	0.71**	0.97 (0.01)	0.89**

TABLE 6. Genetic (r_a) and phenotypic (r_p) correlations between early age height growth traits and selected 8-year traits in Fraser fir

Early age trait	8-year trait							
	USDA grade		Total height		Wholesale value		Height class	
	r_a	r_p	r_a	r_p	r_a	r_p	r_a	r_p
0-year height ^a	-0.04 (0.12)	-0.06**	0.79 (0.04)	0.33**	0.57 (0.08)	0.22**	0.74 (0.03)	0.41**
1-year height	-0.08 (0.11)	-0.12**	0.82 (0.03)	0.43**	0.61 (0.08)	0.34**	0.77 (0.05)	0.48**
0- to 1-year height growth	-0.21 (0.12)	-0.19**	0.75 (0.05)	0.34**	0.60 (0.09)	0.36**	0.73 (0.06)	0.40**
4-year height	-0.31 (0.09)	-0.21**	0.89 (0.02)	0.72**	0.81 (0.08)	0.64**	0.93 (0.03)	0.72**
0- to 4-year height growth	-0.60 (0.09)	-0.20**	0.95 (0.01)	0.67**	0.85 (0.03)	0.62**	0.96 (0.02)	0.68**

NOTE: Standard deviations of the genotypic estimates are given in parentheses.

** , phenotypic correlation significant at the 0.01 level.

^a0 year height is that at time of planting, i.e., field age = 0.

($r_a = -0.61 \pm 0.08$, $r_p = -0.35$); the two direct determinants of wholesale value. Clearly, height class and quality are genetically and phenotypically favorably associated; they do not act as independent traits. Consequently selection of trees by height class alone would indirectly select for superior quality, i.e., USDA grade; a relationship of tremendous value to both breeders and the Fraser fir industry. Similar relationships in Virginia pine led Warlick et al. (1985) to conclude that all Christmas tree traits would be improved if height were used as a sole selection criterion.

Genetic and phenotypic correlations between early age height growth traits and 8-year total height, height class, and wholesale value proved favorable and generally strong (Table 6). However, while the 4-year measures were also moderately correlated with 8-year USDA grade, both 0- and 1-year height showed no real genetic correlation with it. Early selection on either 0- or 1-year height would be expected to have no effect on 8-year grade.

It is particularly noteworthy that height growth from 0 to 4 years shows stronger genetic correlations with 8-year total height and value than does total 4-year height. Removing preplanting influences from 4-year height provides a superior indicator of the genetic potential at rotation age. Variation in planting height is under a lower degree of genetic control ($h_i^2 = 0.17 \pm 0.03$ (Li 1985)) than later height measures. Consequently, correction of 4-year height for planting height seems to eliminate a source of environmental variation.

These results indicate good potential for early age culling in future Fraser fir genetic tests, based on the good genetic correlation of both height at year 0 and height at year 1 with 8-year wholesale value. Such culling could provide far greater selection intensities for little additional expenditure of resources.

Very high genetic correlations of both 8-year wholesale value and height class with 4-year height, and also with

height growth from 0 to 4 years indicate excellent potential for early selection in Fraser fir Christmas trees. Height measurements at the time of planting and 4 years later would characterize most of the genetic potential at rotation age for both height class and wholesale value. Such an early age selection, at half rotation for Fraser fir, could be highly beneficial to breeders interested in rapid generation turnover, minimization of progeny testing costs, and maximization of gain per unit time. As mentioned above, such potentials will be analyzed more elsewhere.

Conclusions

Significant genetic variation between both seed sources, and families within seed sources combined with moderate to strong heritabilities in Fraser fir Christmas trees have been revealed in this study. Very important genetic gains should be achievable from selection and breeding with this species. Selection of a greater proportion of individuals from better performing seed sources should strengthen these gains, as genetic control of important traits in such sources tended to exceed levels averaged overall.

Of all the traits assessed at age 8, only height class and USDA grade may warrant assessment in future tests. Other Christmas tree traits were favorably and moderately to strongly correlated with these two value determining traits. Employing height class as a sole selection criterion for Fraser fir Christmas trees would result in simultaneous improvement of all important traits.

The strength of correlations between early age height growth parameters and 8-year height class, USDA grade, and wholesale value indicate real potential for early age selection in Fraser fir tests. Given the high annual investment required in Fraser fir Christmas tree culture, early age selection will offer a significant reduction in resources required for testing.

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