Determination of relative economic weights for multitrait selection in coastal Douglas-fir[1]

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Abstract: Relationships between tree traits and tree value for lumber production were investigated. For the purposes of estimating relative economic weights for use in multitrait selection in coastal Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), tree height, diameter at breast height, and branch diameter were measured on 164 trees (ages 36–66 years). Increment cores from a subsample (92) of these trees were assayed by X-ray densitometry to determine wood density. Bole volume was derived by summing the log volumes of all logs from each tree. Value of lumber recovered from each tree was determined in a separate mill study using both visual and machine stress rated (MSR) grading rules. Multiple linear regression was used to relate tree value to the growth and wood quality traits. Stem volume and branch diameter significantly influenced tree value under visual grading, with relative economic weights of 0.06 dm^3 and –5.22 cm, respectively. Wood density significantly influenced tree value under MSR grading (relative economic weights: 0.06 dm^3, –6.69 cm, and 0.06 kg/m^3, respectively), where lumber strength is measured more accurately. These regression coefficients can be used directly as economic weights in selection indices.

Résumé : Les auteurs ont étudié les relations entre les caractères propres à l'arbre et la valeur de l'arbre pour la production de bois de sciage, chez le sapin de Douglas de la côte (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*). Afin d'estimer leur poids économique relatif dans la construction d'un indice de sélection multi-critères, la hauteur de l'arbre, le diamètre à hauteur de poitrine et le diamètre des branches ont été mesurés sur 164 arbres âgés de 36 à 66 ans. Des carottes ont été prélevées sur un sous-ensemble de ces arbres (92) pour déterminer la densité du bois à l'aide de la méthode de densitométrie aux rayons X. Le volume du fût a été estimé en additionnant le volume des différentes billes de chaque arbre. La valeur du bois provenant de chaque arbre a été déterminée dans une étude distincte en usine à l'aide de normes de classement visuel et de contrainte mécanique (CM). Les auteurs ont utilisé la régression linéaire multiple afin d'établir la relation entre la valeur de l'arbre et les caractères de croissance et de qualité du bois. Le volume de la tige et le diamètre des branches affectaient significativement la valeur des arbres déterminée par classement visuel, avec des poids économiques relatifs de 0,06 dm^3 et –5,22 cm, respectivement. Avec la méthode de classement CM qui mesure de façon plus précise la résistance mécanique du bois, la densité du bois affectait significativement la valeur des arbres (poids économiques relatifs de 0,06 dm^3, –6,69 cm et 0,06 kg/m^3, respectivement). Ces coefficients de régression peuvent être utilisés directement comme poids économiques dans les indices de sélection.

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Introduction

Choosing the traits or characteristics that will define the best genotypes for use as parents in advanced generation breeding is a critical step in any forest tree improvement program. Many attributes of a tree can be measured, but for selection to be most effective, the number of traits must be limited to those few that significantly influence the yield and quality of desired wood products. This requires a knowledge of end-use product requirements and how tree characteristics and wood properties affect those requirements. The most effective means of selecting to improve overall merit is to combine information on the economic importance of traits and their genetic potential (Hazel and Lush 1943).

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) is the primary species under intensive management on the Pacific Coast of North America; its wood is valued for high-quality building and construction materials (Oswald et al. 1986; USDA 1987). The U.S. market for structural lumber is expected to continue to be strong well into the future (Haynes and Fight 1992). Because of the increasing availability of inexpensive wood products from other species, the greatest demand for Douglas-fir is expected to be in the high-quality lumber market (Ernst and Fahey 1986; Barbour and Kellogg 1990).

Three traits are important in determining the yield and quality of Douglas-fir lumber. Stem size (volume) is related to both yield and lumber grade; wood density and the size

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and frequency of knots are critical to both the strength and appearance of lumber (Kellogg and Kennedy 1986). Wood density is a simple, reliable measure of the amount of cell wall material present in a piece of wood; it reflects the size of individual cells and thickness of the cell wall. Wood density is the single most important physical characteristic of wood for wood products because it is an excellent predictor of strength, stiffness, hardness, and paper-making capacities (Megraw 1985). The distorted grain around knots lowers compression strength of wood parallel to the grain and also lowers bending strength (Desch and Dinwoodie 1981). The goals of genetic improvement of Douglas-fir for lumber production, therefore, are to increase stem volume production per unit of time, maintain high wood density, and limit knot size.

Although the importance of wood density and branch diameter to the value of wood products is well known, these traits have only recently been considered for inclusion in Douglas-fir tree improvement programs (Gonzalez and Richards 1988; King et al. 1988; Vargas-Hernandez and Adams 1991). The emphasis of tree improvement programs in the past has been primarily on stem volume growth. Increasing interest in wood quality traits has been fueled by a growing concern that the harvest of young trees with more low-density juvenile wood will result in lower wood quality and, consequently, reduced lumber grade and value (Kellison et al. 1985; Barbour and Kellogg 1990).

A multitrait selection procedure is needed to select simultaneously for improvement in more than one trait. The selection index approach is the most effective multitrait selection method for improvement in overall merit (Smith 1936; Hazel 1943). Genetic gain in overall merit is maximized by placing emphasis on each trait according to its economic value, heritability, and correlations with other traits. A composite trait or index is developed for each candidate tree and trees are then ranked according to their index values. The use of the selection index method has increased in forest tree breeding in recent years with the availability of computers to facilitate the extensive computations involved (Bridgwater et al. 1983; Christophe and Birot 1983; Dean et al. 1983, 1986; Chollet and Roman-Amat 1987), but it has had limited application to coastal Douglas-fir. The lack of reliable estimates of the relative economic values of individual traits in Douglas-fir and of economic weights based on tree value has been the main barrier to the full implementation of index selection in forest tree breeding (Bridgwater and Stonecypher 1979; Zobel and Talbert 1984; Cotterill and Jackson 1985). Given that stem size, branch size, and wood density all affect lumber quality and quantity, the degree of emphasis (economic weight) placed on each trait when considered simultaneously in a selection program will depend on the relative influence of the trait on the overall merit or worth of an individual tree (Hazel and Lush 1943).

To estimate economic weights on the basis of economic value, the best sources of information are product recovery studies in which the volume and value of products milled from individual trees have been recorded (Ernst and Fahey 1986). A multiple linear regression model can be used to relate the traits of a tree to the value of the products milled from the tree (Baker 1986, chap. 9). The estimated partial regression coefficients in this model represent relative economic weights of the traits and can be used directly in index selection (Cotterill and Jackson 1985). Economic weight estimates may vary with the wood products milled from the trees measured in a recovery study, the grading methods applied, and the pricing structure used. It is important, therefore, to base these estimates on the products that are expected to be in demand in the future, under grading systems that will continue to be industry standards, and under pricing structures that reflect relative differences between grades. There are few examples where relative economic weights based on product value have been reported for commercial tree species because product recovery studies are expensive and labor intensive (Bridgwater and Stonecypher 1979; Kellogg and Warren 1984; Talbert 1984; Cotterill and Jackson 1985; Chollet and Roman-Amat 1987). No product value based economic weights have been reported previously for Douglas-fir. A product recovery study sponsored by the Douglas-fir Stand Management Cooperative (SMC) (Fahey et al. 1991) provided an opportunity to estimate relative economic weights on the basis of the production and grade of Douglas-fir lumber. The SMC is a consortium of State, Provincial, private industrial, and university land management organizations. The usefulness of this approach is dependent on the relationship between the two lumber grading systems in use in the United States and the wood quality traits used to determine grading rules.

Lumber grade is strongly influenced by both wood density and knot size. The visual grading system is the most commonly used method of grading in North America. Visual grading considers knot size, knot placement, and mechanical and biological defects (Western Wood Products Association (WWPA) 1988). For any given width of board, grade decreases as the size of the knots increases. For the highest grades of visually graded structural lumber (Select Structural, No. 1, or No. 2), both physical properties and appearance are important. In addition, acceptable knot size is limited and a minimum number of rings per inch is set to exclude wood of low density.

In mechanical or machine stress rated (MSR) grading, each board is visually examined for defects that would limit strength and mechanically tested for dynamic modulus of elasticity (MOE) (Galligan et al. 1977). The distance that knots are displaced from the edge of the board sets the upper limit of predicted fiber stress in bending, F_b; MOE is used to evaluate strength up to that limit. Wood density and knot size are correlated with MOE and F_b (Grant et al. 1984; USDA 1987). MSR grading provides a more accurate and objective assessment of wood strength than does visual grading, but it is more costly. MSR grading is presently used only for materials that must meet exact design criteria; its use in Douglas-fir, however, is expected to increase in the future, especially for structural lumber (Kellogg 1982).

Our objectives in this study were to (*i*) develop linear regression models that best predict whole-tree dollar value of Douglas-fir lumber as determined by the visual and MSR grading systems from measurements of tree size, branch size, and wood density, (*ii*) estimate relative economic weights for the traits in the above analysis that most influence lumber value of Douglas-fir, and (*iii*) determine the extent to which relative economic weights are a function of lumber grading system.

Table 1. Mean and coefficient of variation for traits measured on individual Douglas-fir trees.

Trait	Sample size	Mean ± SD (range)	Coefficient of variation
Height (m)	164	32.5±4.6 (20.8–45.5)	14.2
DBH (cm)	164	45.6±12.7 (22.9–71.1)	27.9
Average wood density (kg/m^3)	92	493±44.9 (404–658)	9.1
Branch diameter (largest limb, cm)	159	3.5±1.8 (1.3–9.6)	52.1
Tree volume (dm^3)	164	1877.1±1041.3 (303.0–4431.6)	55.5

Table 2. Dollar values of nominal 2 × 4 in. (38 × 91 mm) and 2 × 6 in. (38 × 143 mm) lumber used in this study by grading system (WWPA 1989).

Grade	$/1000 board feet (1.55 m^3)
Visual	
Select structural	240
No. 1	220
No. 2	200
No. 3	140
Economy	80
MSR	
2100F_b	280
1650F_b	240
1450F_b	200

Materials and methods

Sample trees

Materials used in this study were derived from a lumber recovery study sponsored by the Douglas-fir SMC (Fahey et al. 1991). The 236 trees were sampled from 15 intensively managed stands with a wide range of site attributes, growing conditions, ages, and stocking histories in western Washington and Oregon. Trees within stands were chosen to provide a sample of logs with a wide range of stem sizes, limb sizes, and proportions of juvenile wood. Mean tree age ranged from 25 to 85 years.

For the present study, a subset of 164 trees, aged 36–66 years, from 11 stands was used. This was done to remove the confounding effect of age on tree value apparent during examination of scatterplots which revealed a moderate correlation between age and tree value as estimated by either visual (0.60) or MSR grading (0.65).

Measurements

Total tree height and diameter at breast height (1.37 m, DBH) were measured and one 9-mm wood core was taken from each tree at breast height to estimate wood density (Table 1). Not all core samples extended from pith to bark, and cores missing more than 10% of the annual rings were discarded. This accounts for the lower sample size for wood density (92 trees). Individual ring density was estimated with the use of direct-scanning X-ray densitometry (Hoag and McKimmy 1988) on extracted core samples at 9% equilibrium moisture content based on mass and volume at room conditions, not weighted.[4] Average wood density of each tree at breast height was estimated by summing the products of the mean density of each ring by its corresponding ring width and dividing by the overall length of the core.

Trees were felled and bucked to a top diameter of 15 cm at the logging site and were further bucked into mill-length (4–8 m) logs at the mill. Branch diameter was estimated by measuring the diameter, inside the bark, of the largest limb, live or dead, in the butt log of each tree; two caliper measurements were taken at right angles to each other and averaged. Live limbs were measured just above the branch swell and dead limbs flush with the bark. Volume was calculated by summing the inside-bark volumes of the mill-length logs. Gross cubic log volume of the butt log was computed with a butt log formula (Bruce 1982). For all other logs, the Smalian formula was used (Meyer 1953).

Lumber processing

All logs were sawn into 2 × 4 in. (38 × 91 cm) and 2 × 6 in. (38 × 143 cm) lumber at a state-of-the-art sawmill in western Washington (Fahey et al. 1991). This limited product mix was used to help ensure that lumber recovery would reflect the inherent quality of the wood, not the skill of the sawyer in offsetting the effect of branch size on log quality by sawing logs with larger knots into wider boards; in addition, most MSR-graded lumber is marketed in these two sizes. Recovery of chips and sawdust was measured in the log study, but was not considered in the present analysis because the contribution of chips and sawdust to log value varied little within the limited range of tree sizes used.

Lumber was graded both visually and under the MSR grading system. Under the visual system, 2 × 4's were graded by the structural light framing rules and 2 × 6's were graded by the WWPA rules for structural joists and planks (WWPA 1988). To set the MSR grade, each board was first assigned an F_b (extreme fiber stress in bending) class by a lumber grader using the MSR visual grading requirements (WWPA 1988). Boards meeting minimum visual grade criteria for MSR were machine tested and both average and low point of MOE were recorded. Boards not meeting minimum MSR criteria retained the dollar value that had been assigned during visual grading, and this value was used in the summation of board values to estimate MSR tree dollar value.

In the Douglas-fir lumber industry, structural grades No. 1 and No. 2 and Select Structural are often combined into one grade, No. 2 and Better, for sales purposes. More lumber is sold in this grade mix than in any other. We used the index price of No. 2 and Better ($200/1000 board feet (1.55 m^3) in 1989) as the basis for determining the prices of other grades in both grading systems. This price was used for No. 2 grade (visual) and 1450 f grade (MSR). WWPA reports of sales in 1989 and consultations with producers of MSR-graded lumber (Table 2) (WWPA 1989) were used to set price ratios for other grades. This pricing structure was used to gain a generalized picture of the premium for quality apart from the current pricing structure (wherein No. 2 grade and above are combined) and to reflect the expectation that premiums for superior quality structural items will increase slightly over the next

[4] R. Krahmer, E. Lowell, and M. Hoag. 1988. Stand Management Cooperative OSU X-ray densitometer analysis of breast height increment core samples. For. Prod. Dep., Oregon State University, Corvallis, Oreg. Unpublished report.

Table 3. Partial regression coefficients for Douglas-fir as determined by multiple regression for two response variables.

Model	Response variable	Trait	Partial regression coefficient (SE)	95% confidence interval	Coefficient of parietal determination	
					R_a^2 [a]	R_a^2 [b]
1	Dollar value,	Intercept	11.775		0.92	
	whole tree,	Volume	0.060 (0.0002)	0.057 to 0.065		0.89
	visual grading ($VSL)	Branch diameter	–5.225 (0.889)	–7.141 to –3.606		0.92
2	Dollar value,	Intercept	–14.557		0.89	
	whole tree,	Volume	0.058 (0.002)	0.054 to 0.063		0.83
	MSR grading	Branch diameter	–6.693 (1.035)	–8.751 to –4.636		0.88
	($MSR)	Wood density	0.065 (0.031)	0.004 to 0.126		0.89

[a]Adjusted coefficient of multiple determination.
[b]Cumulative adjusted coefficient of multiple determination for the variable and any variables preceding it in the model.

40 years (Haynes et al. 1988). The British Columbia Ministry of Forests took a similar approach in a financial study of the genetic improvement of wood quality in Douglas-fir[5] and in the development of the pricing structure for TREEVAL2, a computer model designed to estimate net product value of individual Douglas-fir trees (Briggs and Fight 1992).

Analysis

We used a stepwise multiple regression procedure (Neter et al. 1983, chap. 12) to build a regression model that would best predict whole-tree dollar value and to estimate partial regression coefficients for use as relative economic weights in genetic selection. The tree trait measurements for total tree height, DBH, stem volume, branch diameter, and wood density were used in the model. The multiple regression equation takes the following general form:

$$[1] \qquad Y = c + a_1X_1 + a_2X_2 + a_jX_j + \ldots + a_nX_n$$

where Y is the dollar value of individual trees, c is the y-intercept (a constant), X_j is the phenotypic value of the jth trait, and a_j is the partial regression coefficient (economic weight for the jth trait). The economic weights, a_j, estimate the amount that the dollar value of a tree changes when the phenotypic value of the jth trait is increased by one unit of measure and the other traits are held constant.

A sequence of regression models was built and, using backward stepwise regression (Sokal and Rohlf 1981, chap. 16), each independent variable was automatically dropped (or readded) when the F-statistic was at $P < 0.05$ to test the hypothesis H_0: $a_j = 0$, where a_j is the regression coefficient for the independent variable, X_j. Height, DBH, volume, branch diameter, wood density, and the two-way interactions between these traits were tested as independent variables. Testing for lack of fit revealed that linear regression functions adequately fit the data as measured by the appropriate F-statistic, and therefore, polynomials were not tested as independent variables because they would account for little additional variation in the response variables (Neter et al. 1983, chap. 4).

Response variables were created for the dollar value of an individual tree on the basis of both the visual grading system ($VSL) and the MSR grading system ($MSR). For both variables, the dollar value of all boards milled from an individual tree was summed to estimate the value of the tree. Manufacturing costs were not subtracted from the dollar value. As in the SMC product recovery study (Fahey et al. 1991), the rationale was to formulate a generalized picture of the role of measured traits in determining tree value without the influence of the harvesting or manufacturing costs of a particular company. This is consistent with the approach used in the development of relative economic weights for loblolly pine (*Pinus taeda* L.) (Talbert 1984).

Inspection of residual plots of both the $VSL and $MSR response variables revealed that error variance increased with increasing stem volume. Therefore, the residual terms in the $VSL and $MSR models were weighted by $1/(\text{volume})^2$ following the method of weighted least squares (Neter et al. 1983, chap. 5). The adjusted coefficient of multiple determination, R_a^2, was used to measure the amount of variation in tree value explained by each model (Neter et al. 1983, chap. 7).

Results and discussion

Predicted whole-tree dollar value

For both response variables ($VSR and $MSR), once individual traits were included in the regression model, interaction effects did not explain significant additional variation. Tree dollar value based on visual grading analysis ($VSL) was best predicted by volume and branch diameter (model 1, Table 3), and most of the variation in whole-tree dollar value was explained by this model (R_a^2 = 0.92). An examination of the cumulative R_a^2 (Table 3) showed that volume alone explained much of the variation in $VSL.

Tree dollar value based on MSR grading ($MSR) (model 2, Table 3) was best predicted by volume, branch diameter, and wood density, and the total amount of variation explained was comparable with that of model 1 (R_a^2 = 0.89). As in the $VSL model, volume was by far the best single predictor of $MSR, followed by branch diameter, as revealed by cumulative R_a^2 (Table 3). Wood density explained a small, although statistically significant, percentage of the variation in $MSR. The fact that wood density accounted for only a small additional portion of the variation in $MSR may be due in part to the low coefficient of variation of wood density in this study compared with the other traits (Table 1).

[5] P.A. Jefferson. No date. Financial evaluation of genetic improvement of wood quality using the SYLVER models: an evaluation for test case traits. B.C. Forest Service. Unpublished report.

Because height and DBH were both highly correlated with volume (Aubry 1992), those variables accounted for little additional variation in either $VSL or $MSR when volume was already in the model; thus, neither height nor DBH was selected as dependent variable by stepwise regression.

Volume was a significant predictor of whole-tree dollar value under both the visual and MSR grading systems (models 1 and 2, Table 3), which illustrates the effect that tree size had on the number of pieces, and therefore on the value, of lumber milled from each tree. Volume was a composite trait of height and DBH; the size of the stem determined the number of logs per tree (height effect) and the number of boards per log (diameter effect). Both number of logs and number of boards per log varied from 1 to 6 (mean = 4) and from 6 to 97 (mean = 36), respectively, among trees in this study. This wide variation clearly had a major impact on tree value.

Branch diameter was important in predicting the value of trees for both response variables. This was to be expected, considering the direct impact that branch diameter has on lumber grade. The unfavorable correlation between branch diameter and volume (Aubry 1992) indicates, however, that selection for one trait will have an adverse impact on the other.

Relative economic weights

The partial regression coefficients determined for each trait (Table 3) can be used directly as economic weights in index selection. Relative economic weights based on product value have been reported for various combinations of stem size and quality traits in a few forest tree species, including stem height, diameter, volume, and straightness in loblolly pine (Bridgwater and Stonecypher 1979; Talbert 1984), stem height, diameter, straightness, and branch diameter in radiata pine (*Pinus radiata* D. Don) (Cotterill and Jackson 1985), and log diameter and basal sweep in maritime pine (*Pinus pinaster* Aiton) (Chollet and Roman-Amat 1987). A common feature in all these studies and in the results presented here was the inclusion of a trait representing tree size or yield and at least one quality trait in the models developed to estimate economic weights. Other than this general observation, contrasts or comparisons between the results of this investigation and former studies estimating economic weights are not possible due to differences in tree species, tree age, traits considered, formulation of response variables, and the type of product modeled.

The choice between the economic weights in models 1 and 2 for application in index selection represents a decision on whether to include wood density in a selection program. Previous studies have shown that selection for volume alone will reduce wood density in coastal Douglas-fir (King et al. 1988; Vargas-Hernandez and Adams 1991). Maintaining or increasing the quality of Douglas-fir lumber is imperative if this species is to continue its dominance in the structural and building product market. Given the negative correlation between stem volume and wood density, losses in wood strength are inevitable if increased volume is the only criterion for genetic selection. Wood density had little effect on tree value as determined by visual grading. Wood density is critical to wood strength, however, which was reflected in the economic weights based on MSR grading. We predict that MSR grading will be more widely used in the near future, particularly for structural lumber, because it provides an accurate, objective evaluation of wood strength (Kellogg 1982).

Several factors need to be considered when contemplating the application of specific economic weights (Lin 1978; Cotterill and Jackson 1985). One concern is that the weights will change with the definition of the product. For example, if the product mix was vastly different from the 2 × 4 and 2 × 6 in. combination described here, the economic weights developed in this study would probably not be applicable. If the goal of Douglas-fir management was changed to maximization of fiber production, for example, changes in the weights might be expected. However, the use of Douglas-fir for products made from pulp has historically been very low (Larsen and Bearden 1989). In this study, it was assumed that coastal Douglas-fir is primarily used for structural lumber and other building materials; this assumption is certainly true for today and is expected to be the trend in the future.

There is also the concern that the pricing structure used in this study may not reflect that of future markets. Although absolute lumber values may rise or fall, relative values are expected to remain the same (Haynes and Fight 1992). Changes in lumber prices over time did not change the relative value of tree quality classes in a log study of interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) (Middleton et al.1985). Also, since the values of all the boards milled from a tree are added to calculate tree value, only large changes in the relative value of each grade would alter the outcome of this study.

Grading system

The presence of wood density in the model predicting $MSR, but not in the model predicting $VSL, reflects the way wood strength is assessed in these two grading systems. Lumber strength is measured directly by machine testing in MSR grading; strength is positively correlated with wood density. In visual grading, wood density is considered indirectly by limiting growth rate to four rings per inch in the higher grades. In this study, however, almost all of the logs met this growth rate criterion, so individual piece lumber value, under visual grading, was determined primarily by branch diameter.

Conclusions

Our study illustrates the effect that variation in volume, branch diameter, and wood density have on tree value based on structural lumber. The results also demonstrate the need to consider these three traits in the development of advanced breeding programs of coastal Douglas-fir. At present, most Douglas-fir tree improvement programs use volume as the primary criterion for selection, since volume is recognized as the strongest determinant of tree value and because branch diameter and wood density are expensive to measure. Simultaneous selection in Douglas-fir for improvement in all three traits provides a challenge to the tree breeder because of the adverse genetic correlations between these traits. It is impossible to maximize gain in all three traits and very difficult to predict the outcome of index selection. Therefore, the relative importance of these traits in selection for overall merit can only be assessed when genetic and phenotypic parameter estimates are combined with economic weights to predict the outcome of using multitrait selection indices in breeding populations.

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