A Hedonic Approach to Value *Pinus radiata* Log Traits for Appearance-Grade Lumber Production

Rosa M. Alzamora and Luis A. Apiolaza

Abstract: This study used a hedonic approach to estimate the economic value of radiata pine log attributes (small-end diameter, form, and internode length) for appearance-grade lumber, including molding and better, shop, and industrial finger joint. Models were also built at the tree level to investigate the effect of selection as conducted by breeders. A Chilean sawing study provided information on wood traits and log out-turn for 156 logs divided into three classes: pruned butt log, second log, and third log. The conversion return of logs, instead of log prices, was used as the measure of log economic value. The economic values of log small-end diameter were 0.33, 0.19, and 0.10 US$/mm for the first, second, and third log, respectively. Concerning form, those values were US$2.6, US$1.4, and US$0.63 for a marginal improvement of this characteristic. The value of mean internode length was 0.19 US$/cm for second unpruned logs. Values for other internode length indices are also presented in this article. Branch variables were not statistically significant to explain the log recovery value. Finally, log recovery value was found to be elastic to the changes in small-end diameter and form, but inelastic to changes in the mean internode length. FOR. SCI. 56(3):281–289.

Keywords: wood attributes, hedonic values, *Pinus radiata*, appearance lumber, breeding objectives

LOG ATTRIBUTES, including volume and form, have a large influence on the yield and quality of lumber. Most attributes can be identified and measured, but their economic values are not well understood nor are they frequently reported. For example, advances in the assessment of wood stiffness and resin defects of appearance products have contributed to improved log segregation practices (Ridoutt et al. 1999, Walker and Nakada 1999, Lindström et al. 2002, Lasserre et al. 2005, McConchie and Cown 2008). The economic value of wood characteristics has received less study. However, knowing the value of wood traits is very important if growers are to improve the quality of the forest crop.

Economic values are particularly important to tree breeders, as they require this information to define breeding objectives and to build selection indices. Commonly, bioeconomic models have been used to obtain those values, modeling the effects of trait changes on the profitability of a production system (Borralho et al. 1993, Apiolaza and Garrick 2001, Ivković et al. 2006). Other approaches used to obtain economic values of traits have been linear programming (Ladd and Gibson 1978), efficiency measures on production systems (e.g., Lambert and Wilson 2003, Todoroki and Carson 2003), and hedonic models (e.g., Bloomberg 2001).

Hedonic values are defined as the implicit prices of traits, and they are revealed by observed prices of differentiated products and the specific amounts of traits associated with them (Lancaster 1966, Rosen 1974). In the case of agricultural commodities, hedonic models have been applied to determine the marginal value of quality traits (Ladd and Martin 1976, Ethridge 1982, Angel et al. 1990, Espinosa and Goodwin 1991, Bowman and Ethridge 1992, Parker and Zilberman 1993, Nerlove 1995, Carew 2000, Walburger 2002).

When breeding objectives for specific wood attributes are developed, comparable approaches to hedonic models have been occasionally applied under the name "value regressions." For instance, Ernst and Fahey (1986) stated that regressions of value on wood traits, coming from product recovery studies, would provide the way to estimate economic weights for tree breeders. Similar studies have been documented by Cotterill and Jackson (1985) and Aubry et al. (1998). Forest hedonic models have mostly been concerned with the impact of environmental amenities on land prices (Munn and Palmquist 1997, Bastian et al. 2002, Snyder et al. 2007) and also with factors that explain stumpage price (e.g., Puttock et al. 1990).

This article presents an application of hedonic models to value log and tree wood attributes for appearance lumber of *Pinus radiata* D. Don in Chile. The log recovery value is used as the response variable instead of log prices. Finally, the sensitivity of the log value to wood attribute changes is analyzed using an elasticity approach.

Materials and Methods

The data for this project came from a Chilean sawing study that included 156 radiata pine logs from three stands. At the time of sampling the stands were 19, 22, and 34 years old with site indices of 31, 28, and 27 m, respectively. These radiata pine stands are representative of the site quality

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available for clear wood production. The stands were thinned and pruned to different stocking intensities, but all of them targeted a 5-m long pruned log. Trees used in the current study were chosen with consideration of representativeness in the diameter distribution as well as stem quality to generate sawlogs. The log sample contained a minimum small-end diameter of 20 cm, and most trees contained three 5-m logs. Table 1 summarizes quality information at the log level.

Definition of Tree and Log Variables

SED, presented in Table 1, is the small-end diameter of the log. FORM corresponds to the relationship C_{vol}/L_{vol}, where C_{vol} is the common volume (m^3) equivalent to the maximum cylinder contained in the log, and L_{vol} is the under bark log volume. SED and FORM are related to the recovery of solid wood during log processing. Branch index (BI) is the mean diameter of the four largest branches of the log, one per quadrant (north, east, west, and south). Largest branch (LB) is the diameter of the largest branch of the log. Defect core diameter (DCD) corresponds to the diameter with defects after pruning. The prune log index (PLI) is an indicator that expresses the potential of a pruned log to produce long clear wood pieces, such as molding and better (Park 1989). PLI is estimated by the relationship,

$$\text{PLI} = (\text{D1.3} - \text{DCD})^{0.5} * (\text{D1.3}/\text{DCD}) * \text{FORM}^{1.6}, \quad (1)$$

where D1.3 is the diameter at 1.3 m of log. Usually, the DCD is known after processing the log; nevertheless, it can be previously estimated by using PLI or by statistical models that consider variables related to the silvicultural regime of the stand (Knowles et al. 1987).

Internode length is an important characteristic in determining the out-turn of shop and industrial finger joint grades. The mean internode length (MIL) is the sum of length (m) of internodes in branched sections of the log divided by the number of internode lengths in branched sections of the log (Watt et al. 2000). Internode index (II_b) is the sum of internode lengths greater than a given base (b) divided by the log length. This study considered bases of 60 and 80 cm. Further details relating to the above traits are described in the literature by Park (1989), Grace and Carson (1993), Carson and Inglis (1988) and Jayawickrama et al. (1997). The base internode length (BIL) corresponds to the minimum internode length that is contained in 50% of the log length. Meneses and Guzmán (2003) developed this index for unpruned logs based on the internode index (II_b). Thus, BIL represents that minimum internode length (b) that generates an II_b equal to 0.5.

Table 1. Average value of log descriptors segregated by log class

Variable	Pruned butt log	Second log	Third log
No. logs	54	57	45
Log length (cm)	505	505	410
SED (mm)	385.15	358.60	335.09
Log volume (m^3)	0.73	0.55	0.43
FORM	0.73	0.79	0.79
DCD (mm)	240.69		
PLI	4.83		
BI (mm)		44.95	50.46
LB (mm)		56.64	66.55
BIL (cm)		71.31	52.42
MIL (cm)		71.44	58.12
II_{80} (%)		33.04	23.49
II_{60} (%)		46.77	32.16

II_b, MIL, and BIL give complementary information about internode length. MIL describes the average internode length of a log, tree, or stand, whereas II_b provides an indication of variability, but it is usually estimated for specific internode lengths, which limits the possibilities of processing to a limited set of products. BIL is more flexible and is associated with the length of clear pieces that could be obtained from the logs, which is useful for matching stands of varying internode length to product requirements (Meneses and Guzmán 2003).

The variables included in the models correspond to log traits that are important in the recovery of radiata pine appearance grades (e.g., Zhang 1997, Beauregard et al. 2002, Young et al. 2004). In addition, these attributes have been proposed as breeding objectives to produce solid wood owing to their influence on log value recovery (e.g., Shelbourne 1997, Shelboume et al. 1997, Ivković et al. 2006).

Sawmill Product Evaluation

Once the standing trees and logs were assessed in the field, the logs were processed at the mill. The aim of processing was to maximize the recovery of lumber in the molding and better grades from the pruned logs and shop grades from unpruned logs, as described by the (Western Wood Products Association (1995) for the US market. An additional low-quality product called finger out was generated by the sawing study and included in the analysis. Lumber grade recovery for each log type is shown in Table 2.

Model Components

Hedonic models disaggregate the price of a product into the value of its component traits to obtain the contributory value of each attribute (Rosen 1974). Logs are required by processors because they contain wood traits to produce specific lumber. In keeping with hedonic model theory, the log is a differentiated product with attributes that can be identified and measured and, therefore, monetarized.

We assume competitive markets, and the models developed by Ladd and Martin (1976) and Espinosa and Goodwin (1991) are used as a theoretical framework. We also consider a single product firm where specific log attributes, such as small-end diameter, form, and internode length, are arguments in the appearance-grade lumber production function G(*t*).

If the log processor is assumed to maximize profit subject to the production function G(*t*), the first-order conditions of the profit maximization generate Equation 2, which represents a hedonic price function. Lumber production is a function of the log trait use, which is a function of the log use; thus, the differentiation of a compound function (function that operates on another function, often represented as

Table 2. **Descriptive statistics of lumber volume by product**

	Molding and better	3rd clr	Shop 1	Shop 2	Shop 3	Finger joint blocks	Finger out
	(m^3)						
Pruned butt log							
Average	0.179	0.002	0.036	0.045	0.070	0.020	0.022
Maximum	0.613	0.052	0.135	0.191	0.167	0.111	0.063
Minimum	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD	0.147	0.009	0.041	0.046	0.038	0.029	0.024
Second log							
Average	0.027	0.005	0.035	0.083	0.103	0.016	0.030
Maximum	0.371	0.091	0.233	0.388	0.296	0.142	0.095
Minimum	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD	0.069	0.018	0.058	0.089	0.056	0.028	0.282
Third log							
Average	0.001	0.001	0.014	0.137	0.086	0.032	0.026
Maximum	0.025	0.037	0.221	0.413	0.267	0.123	0.065
Minimum	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SD	0.005	0.006	0.043	0.11	0.059	0.033	0.020
Tree							
Average	0.239	0.010	0.096	0.208	0.244	0.068	0.075
Maximum	1.009	0.091	0.442	0.632	0.507	0.178	0.203
Minimum	0.000	0.000	0.000	0.000	0.078	0.000	0.000
SD	0.211	0.022	0.114	0.193	0.099	0.056	0.057

3rd clr, Shop Lumber grade (KD Shop Radiata 3rd Clr 5/4 Hvy 525), also denoted Factory Select.

nested functions, e.g., $f(g(x))$) is used to derive

$$p_z = p * \sum_{t_i=1}^{n} \frac{\partial G}{\partial t_i} * \frac{\partial t_i}{\partial z}, \tag{2}$$

where p_z is the price paid for the input (log) and p is the price received for the product (appearance-grade lumber). Variable z corresponds to the quantity of the input log used in the production of lumber, t_i is the amount of trait i provided by one unit of input z, $\partial t_i/\partial z$ is the marginal yield of trait t_i in the production of lumber from input z, and $p * (\partial G/\partial t_i)$ is the value of the marginal product of trait t_i, which represents the marginal implicit price (hedonic price) paid for trait t_i because of its contribution to lumber production. Thus, Equation 2 states that the price paid for the input log is equal to the sum of the hedonic prices of the log traits multiplied by the marginal yield of those traits.

Equation 2 may be simplified with the assumption that the marginal product of the trait t_i and $\partial t_i/\partial z = T_i$ is constant. This simplification implies that each additional unit of input z contributes the same amount of the tth trait to the function G(t). Thus, Equation 2 can be written as the following single linear hedonic price function:

$$p_z = \sum_{t_i=1}^{n} \beta_{t_i} * T_i. \tag{3}$$

These assumptions have been consistent with many natural commodity traits (Espinosa and Goodwin 1991, Ladd and Martin 1976). Nevertheless, this study is open to estimate nonlinear functional forms according to the model specification tests.

Linking log prices with their attributes by regressions allows one to obtain the parameters of Equation 2, which is the foundation of hedonic models. If attributes are not reflected in prices, but they are observable, measurable, and directly related to the quality and value of final products, an alternative approach of value could be used to estimate the parameters of Equation 2. For example, log internode length is a trait intimately related to quality and prices of shop products. Thus, longer internodes generate longer shop pieces with higher prices. However, the log market does not explicitly value this characteristic in unpruned log prices.

This study proposes the use of a log recovery value called conversion return (CR), which represents the theoretical maximum willingness to pay for logs in US\$/m^3 delivered to the sawmill (Davis et al. 2004). The suitability of product recovery studies to value wood traits for breeding purposes has been reported by other studies (e.g., Aubry et al. 1998, Ernst and Fahey 1986). This indicator corresponds to the residual value of the log after processing, and it is estimated as

$$\mathrm{CR} = \sum_{i=1}^{N} p_i * L_i - \mathrm{PC}, \tag{4}$$

where p_i is the price of lumber type i, L_i is the volume of lumber type i contained in 1 mm^3 of logs, and PC is the processing cost of 1 m^3. Prices of lumber corresponding to the "Industrials, Specialties, and Other Items" section in the Random Lengths Report (Random Lengths 2008), were directly provided by Random Lengths publications. These corresponded to the monthly prices series 1995–2008, which were expressed in 2008 using the US Consumer Price Index (base 1982–1984:100). The average values of these series were used to estimate the CR. Table 3 presents prices and shipping costs of products, as well as log processing costs (Jean P. Lasserre, pers. comm., Forestal Mininco-Chile, Mar. 20, 2008).

Explanatory variables were measured and estimated from logs and trees. The information at the log level includes SED, FORM, internode indices (MIL, BIL, II_{60}, and II_{80}), and branch measures. However, our hypothesis was

Table 3. Prices and shipping costs for products and processing costs for logs

Molding and better	3rd Clr	Shop 1	Shop 2	Shop 3	Finger joint blocks	Finger out	Shipping cost	Log processing cost
	........(US$/m^3)........							
US$584	394	373	328	266	367	257	60	70

3rd clr, Shop Lumber grade (KD Shop Radiata 3rd Clr 5/4 Hvy 525), also denoted Factory Select.

that branches would have only a minor influence on the quality and value of appearance products, because the knots are removed as part of the production process; i.e., a remanufacturing plant will use chop saws to remove all knots. Thus, the size of knots has a much lower effect than the distribution of knots, which is considered by the internode index. In fact, the requirements for radiata pine appearance lumber relate only to the length of the clear piece (Kretschmann and Hernandez 2006). If there were specific stiffness or strength requirements, the situation would be different because in that case knots derived of branches would cause downgrade in lumber as happens with structural lumber (Chauhan 2006).

At the tree level, the explanatory variables were dbh and internode length indices. Tree form, BI, and products volume per tree were obtained by aggregating the logs for each tree, which meant rebuilding 40 trees.

The suitability of a linear functional form for the hedonic models was assessed by the Box-Cox transformation (Box and Cox 1964). The objective of this transformation is to identify an appropriate exponent (λ) to obtain the best transformation to achieve data normality. The Box-Cox transformation takes the form

$$y(\lambda) = \begin{cases} \dfrac{y^{\lambda} - 1}{\lambda}, & \text{if } \lambda \neq 0; \\ \log y, & \text{if } \lambda = 0. \end{cases} \tag{5}$$

The resulting functional form will depend on the value of λ. For instance, if λ is equal to 1, the transformation is linear.

The hedonic model approach allows estimation of elasticities to assess the sensitivity of log value to changes in wood attributes. The changes in log value and attributes were expressed as percentages of the average log value and average trait. The elasticity of log value (ε) is the change in CR divided by the change in the attribute, multiplied by the level of the attribute divided by the level of CR. In this way, the elasticity depends on the attribute levels considered in its estimation. ε is estimated as

$$\varepsilon_i = \frac{\partial \mathrm{CR}}{\partial t_i} * \frac{t_i}{\mathrm{CR}}, \tag{6}$$

where t_i is a trait in the hedonic model and CR is the conversion return of the log. If this elasticity is <1 (inelastic), there will be a less-than-proportionate change in relative log value for any change in the wood trait. The opposite is true if the elasticity is >1 (elastic), when the proportionate change in relative log value is greater than the change in the trait. Thus, it is desirable that the log attributes that contribute to log value, such as SED, FORM, and internode length, have elasticity values >1.

Results and Discussion

Hedonic models were fit at the log level and tree level, considering attributes of form, diameter, internode length, and branches as well as of silviculture. The hedonic value of a given attribute was calculated as the partial derivative of CR on that attribute. Models presented at the tree level aim to understand the effect of improving wood quality as done by tree breeders in the development of breeding objectives. Furthermore, there is rarely an opportunity in radiata pine to process 14 m of tree for the same end product. This information could help to assess the effect of improvement at the tree level on profitability at the log level.

Log-Level Models

The conversion return averaged 114, 66, and 54 US\$/m^3 for first, second, and third logs, respectively. Log recovery values were consistent with the amount of highest priced lumber that they generated. Thus, the butt log presented the highest value because of its high volume of molding and better products. However, higher differences in value between butt log and second log have been reported (e.g., Beauregard et al. 2002). The smaller difference obtained in this study was due to small piece size, large defect core size, and the associated low PLI (4.8). BI for the second log was 45 mm, lower than that for the third log (50 mm). However, the largest branch was found in the second log (158 mm). Similar results were obtained by Woollons et al. (2002) in a study for developing a branch model for New Zealand radiata pine. In addition, the authors highlight the variability of branch size observed for this species. The high variability of radiata pine branching traits, within trees and among trees, was also reported by Bannister (1962).

Branch size depends on initial spacing and site index (Tombleson et al. 1990). In addition, the combined effects of thinning and pruning could increase branch sizes above the last pruned section (Jacobs 1938 cited by Shirley 1974). This situation could occur when wider spacing is left after thinning, especially in direct sawlog regimes (Chauhan 2006).

Branch data for second and third logs showed a weak (not significant) correlation between BI and MIL of 0.02 and 0.16 for the second and third logs, respectively. If we consider LB, these correlations increased slightly. Our data set does not support the positive relationship between internode length and branch size reported by other studies (e.g., Burdon et al. 1992, Watt et al. 2000). In contrast, Woollons et al. (2002) obtained a low correlation (~0.1) between the size of the maximum branch and internode length. Nevertheless, our data showed a positive correlation between BI and SED, 0.53 and 0.47 for second and third log, respectively.

Longer internodes were observed in the second log. This result agrees with the trend depicted by the model of Grace and Carson (1993) and with the results obtained by Tombleson et al. (1990).

There were six hedonic models fitted at the log level: one for the first pruned log, four for the second unpruned log, and one for the third unpruned log. The explanatory variables for the first log were FORM, SED, and DCD. For the second log the variables were SED, FORM, BI, and one internode measure at the time: MIL, BIL, II_{80}, and II_{60}. Finally, the third log model considered SED, FORM, and BIL as independent variables. The functional form of the hedonic models was assessed by the Box-Cox transformation, obtaining $\lambda = 1$ for all models and making a linear functional form suitable.

Models were not found to be heteroscedastic using the White test, at a significance level of 0.01. The normality of the data was also tested using the Shapiro-Wilk test. Results indicated that there was no evidence to reject the null hypothesis of normally distributed data. Collinearity between explanatory variables was tested by the condition index (CI). This index is a measure of the relative amount of variance associated with an eigenvalue; consequently, a large CI indicates a high level of collinearity (Rawlings et al. 1998, Quinn and Keough 2002). Table 4 indicates the presence of collinearity, especially with variables related to branches and internode length.

The first approach to reduce collinearity was to eliminate those variables with the highest CI values. However, collinearity persisted with the internode length variables, which presented a CI close to 27 in the unpruned log models. Instead, models were fitted by centering the explanatory variables, expressing them as deviations from their mean values. Using this approach, the CI for explanatory variables was reduced to <3, which would suggest no collinearity problems. This centering process does not affect residual standard deviations, goodness of fit, coefficient values, or standard error of the interactions, but its main effect is that the coefficients are now interpretable based on a comparison with the mean of the data (Gelman and Hill 2007).

Models were also tested with the Durbin-Watson statistic (d) to detect autocorrelation in the residuals. The statistic d was >2 for all log models, suggesting that there are no autocorrelation problems.

Table 5 presents the results of the final models. Given the linear functional form of the models, parameters correspond to the trait hedonic values.

The model for the pruned butt log presented an R^2-adj of 0.65, and all coefficients were significantly different from 0 ($P < 0.01$). As expected, FORM and SED had a positive contribution to log value, whereas DCD had a negative role. For this log, 50% of the CR variation was explained by SED ($P < 0.0001$), which supports the economic importance of log size. FORM and SED are inherent attributes of the logs, whereas DCD is a variable generated by silviculture. Despite this difference, DCD was considered in the model because it gives indirect information of the amount of knot-free wood, which is the objective product in the pruned log.

The hedonic values of SED and DCD were 0.33 and −0.27 US$/mm, respectively. These values correspond to the marginal contribution to log recovery value for having an extra millimeter on SED and DCD, in which case they are expressed in US$/m^3. The variable FORM is an index that ranges between 0 and 1; thus, improving this index by 1% would result in an increment of 2.58 US$/m^3 in the log conversion return.

The models for second logs presented high values for R^2-adj (Table 5). All parameters were statistically significant ($P < 0.05$), and their signs were consistent across models. In addition, the magnitude of the coefficients for internode indices followed the expected trend; the highest value is associated with II_{80} followed by II_{60}. Similar results were obtained by Beauregard et al. (2002), but their model considers dbh, BI, and II_{60} as explanatory variables and the resulting goodness of fit was 0.9. These authors did not report the regression coefficients; nevertheless, they pointed out that trees with small branches presented better grade recovery than trees with big branches.

In the second logs the hedonic values for FORM were consistent across models with values between 1.46 and 1.49 US$/m^3. These values were lower than those observed in the first log. This result was expected owing to the higher economic value of the butt log. In fact, 65% of the tree value was contained in the first log. SED presented a consistent hedonic value of ~0.19 US$/m^3 across models, explaining 65% of variation of the CR ($P < 0.0001$).

Regarding the economic value of internodes, the first model fitted MIL with a hedonic value of 0.19 US$/cm. The

Table 4. CI to test collinearity in models at the log level

	CI					
Variables	Model log 1	Model 1 log 2	Model 2 log 2	Model 3 log 2	Model 4 log 2	Model log 3
INTERCEPT	1.000	1.000	1.000	1.000	1.000	1.000
SED	9.624	5.195	4.040	4.424	4.519	4.156
FORM	19.713	7.541	7.320	7.968	7.021	9.742
DCD	34.347					
BI		30.329	29.898	30.245	29.733	
MIL		12.400				
BIL			12.2881			35.524
II_{60}				12.338		
II_{80}					12.154	

Table 5. Hedonic model results, first, second and third log

Models	Parameter estimate	SE	R^2-adj
Pruned butt log: CR = $\beta_0 + \beta_1 \times$ SED + $\beta_2 \times$ FORM + $\beta_3 \times$ DCD			0.65
Intercept	113.656*	2.103	
SED	0.339*	0.059	
FORM	257.900*	55.602	
DCD	−0.267*	0.090	
Second log, model 1: CR = $\beta_0 + \beta_1 \times$ SED + $\beta_2 \times$ FORM + $\beta_3 \times$ MIL + $\beta 4 \times$ BI			0.66
Intercept	66.331*	2.690	
SED	0.189*	0.033	
FORM	145.515*	36.191	
MIL	0.187†	0.080	
BI	−0.043	0.172	
Second log, model 2: CR = $\beta_0 + \beta_1 \times$ SED + $\beta_2 \times$ FORM + $\beta_3 \times$ BIL + $\beta 4 \times$ BI			0.68
Intercept	66.336*	2.628	
SED	0.191*	0.033	
FORM	142.491*	35.376	
BIL	0.159*	0.056	
BI	0.003	0.169	
Second log, model 3: CR = $\beta_0 + \beta_1 \times$ SED + $\beta_2 \times$ FORM + $\beta_3 \times II_{60} + \beta 4 \times$ BI			0.65
Intercept	66.299*	2.716	
SED	0.200*	0.034	
FORM	147.076*	36.544	
II_{60}	22.572†	10.833	
BI	−0.003	0.176	
Second log, model 4: CR = $\beta_0 + \beta_1 \times$ SED + $\beta_2 \times$ FORM + $\beta_3 \times II_{80} + \beta 4 \times$ BI			0.67
Intercept	66.271*	2.636	
SED	0.191*	0.033	
FORM	149.179*	35.486	
II_{80}	27.518*	9.887	
BI	−0.033	0.168	
Third log: CR = $\beta_0 + \beta_1 \times$ SED + $\beta_2 \times$ FORM + $\beta_3 \times$ BIL			0.38
Intercept	54.159*	2.109	
SED	0.099*	0.025	
FORM	62.880‡	32.166	
BIL	0.025	0.065	

* Significant at 0.01 level.
† Significant at 0.05 level.
‡ Significant at 0.1 level.

hedonic value for BIL was 0.16 US$/cm. Internode indices II_{60} and II_{80} presented values corresponding to marginal contributions of 0.23 and 0.28 US$/m^3 to the CR, respectively.

Branch variables did not provide a significant ($P < 0.1$) explanation of recovery value for second logs for appearance lumber. Table 5 shows the information corresponding to BI; models were also tried with LB, which was not significant ($P < 0.1$).

Concerning the third log, 32% of CR variation was explained by SED, which supports the significant economic weight of this trait ($P < 0.0001$). Although the goodness of fit was poor (R^2-adj 0.38), the intercept and parameters associated with SED and FORM were significant ($P < 0.1$) and the corresponding hedonic values were lower that those obtained for the second log. The parameter associated with BIL was not significant; however, its sign was consistent with expectations. In addition, this log presented the highest variability of quality and value among logs, which could be influencing fit.

Tree-Level Models

Two models are presented to explain tree value in terms of wood attributes. The functional form of these models was also linear, with $\lambda = 1$ for the Box-Cox transformation. These models did not present heteroscedasticity problems; nevertheless, there was collinearity between explanatory variables, which was avoided by centering the variables. Concerning autocorrelation, the Durbin-Watson statistic (d) was close to 1.9 for both tree models; which would indicate a mild presence of autocorrelated residuals.

The average conversion return was 175 US$/tree. Models that explained CR at the tree level resulted in an improved fit compared with the models at the log level, with an R^2-adj of 0.92 for both models. Table 6 presents the results of the hedonic models at the tree level.

The explanatory variables considered in these models were dbh, FORM, internode measures, DCD, and BI. The pertinence of dbh and internode length for predicting appearance lumber quality from trees has been also reported by Gazo et al. (2000).

Concerning internode measures, model 1 considered the mean internode length between 5 and 11 m (MIL_{511}). The second model included the base internode length of the second log as the explanatory variable (BIL_2).

The economic values of attributes derived from model 1 were 1.09 US$/cm for dbh and 3.81 US$ for FORM (the highest value for this variable). The value of MIL_{511} was

Table 6. **Hedonic models at the tree level**

Models	Parameter estimate	SE	R^2-adj
Tree, model 1: CR $= \beta_0 + \beta_1 \times$ dbh $+ \beta_2 \times$ FORM $+ \beta_3 \times$ MIL_{511}			0.92
Intercept	175.445*	5.786	
dbh	1.091*	0.092	
FORM	381.197†	144.251	
MIL_{511}	0.115	0.174	
DCD	−0.011	0.159	
BI	−0.115	0.366	
Tree, model 2: CR $= \beta_0 + \beta_1 \times$ dbh $+ \beta_2 \times$ FORM $+ \beta_3 \times$ BIL_2			0.92
Intercept	175.44*	5.556	
DBH	1.049*	0.092	
FORM	374.453†	138.323	
BIL_2	0.213‡	0.116	
DCD	0.054	0.158	
BI	−0.078	0.350	

* Significant at 0.01 level.
† Significant at 0.05 level.
‡ Significant at 0.1 level.

not significant, although its magnitude and sign were as expected. In the same way, DCD and BI were not significant to explain tree recovery value. In model 2, variables dbh and FORM had hedonic values similar to those generated by model 1. The parameter associated with BIL_2 was statistically significant ($P < 0.1$) and higher than the corresponding value at the log level. This difference is due to the higher economic value of trees compared with the value of second logs. In contrast, DCD and BI were not significant and were close to 0.

Although the value of trees could be debatable, they were estimated to show the joint value of the logs that potentially could be processed for appearance products. This information could be useful for breeders, particularly to assess single-purpose versus multipurpose breeding programs.

Elasticity Results

The sensitiveness of CR to log attributes changes can be analyzed using elasticity. Despite the similarity between the elasticity of CR and the attribute economic value, they are different concepts. The value of an attribute obtained by hedonic models corresponds to the marginal contribution of the trait to the CR and is expressed in absolute values (US$/m^3). The elasticity of the CR with respect to one log trait is the percentage change in CR caused by a 1% change in the trait. The changes in CR and attributes are expressed as percentages of the average CR and average attribute. Elasticity is dimensionless, and its interpretation depends on the resulting value being greater than, equal to, or less than 1.

Table 7 presents the elasticities of the log recovery value estimated from two hedonic models. The first one corresponds to the model of the butt log, and the second one is model 1 for the second log (Table 5). Elasticity of the log recovery value was estimated for SED, FORM, DCD, and MIL. The elasticity values for the pruned butt log indicate that the CR was SED and FORM elastic but DCD inelastic. Thus, CR would increase by 1.2% if SED experiences a change of 1%, whereas CR would increase by 1.7% for FORM. Concerning DCD, a change in this variable would cause a less-than-proportional change in CR. Given that this variable has a negative contribution to the log CR, having elasticity <1 is advantageous.

Table 7. **Elasticities for log conversion return on attributes SED, FORM, DCD, and MIL**

Models	Mean attributes values	Elasticity (%)
Pruned butt log model		
SED (mm)	385.148	1.149
FORM	0.730	1.656
DCD (mm)	240.685	−0.565
Second log, model 1		
SED (mm)	358.596	1.027
FORM	0.792	1.737
MIL (cm)	70.786	0.201

Concerning the second log, the CR was SED and FORM elastic, with elasticity values similar to those of the butt log. In contrast, CR was MIL inelastic. Thus, the CR would increase just by 0.2% if the mean internode length increased by 1%.

Elasticity values could be useful complementary information to implement wood attribute rankings in breeding programs. For instance, if a wood attribute has high economic value, and its log value elasticity is >1, then this characteristic will reward breeding effort, as occurs with SED and FORM.

Conclusions

The objective of this study was to estimate the economic value of wood traits of radiata pine logs for producing appearance lumber (molding and better, shop, and industrial finger joint). We used hedonic models to ascertain the economic values of wood attributes on pruned butt logs, unpruned logs, and trees. Finally, an elasticity analysis was used to understand the magnitude and the direction of the log recovery value response due to changes in wood attributes.

The use of conversion return as a response variable made it possible to capture and value marginal changes in wood traits. Thus, despite its theoretical nature, conversion return is a plausible economic measure to assess wood traits at the log and tree levels. Using conversion return, processors incorporate information known that is part of their decision-making process when buying logs.

SED and FORM were the characteristics with the highest economic value for the production of appearance lumber as well as those that generated the highest log value elasticities. This result is consistent with the priorities observed in many breeding programs. The value of internode length indices highlighted their significant contribution to the value of logs destined to be appearance lumber.

Branch variables did not contribute to explaining the variation of CR for unpruned logs. These results supported the hypothesis asserted in this study. In this way, the wood quality of unpruned logs to produce appearance grades should just be focused on SED, FORM, and internode length variables. In addition, appearance products have no requirements for stiffness and strength, a case in which knots generated by branches would negatively affect the log recovery value.

BIL showed good performance in explaining log and tree recovery values. Thus, it would be advantageous to incorporate this alternative index into the information derived from radiata pine unpruned logs.

The elasticity analysis was useful for examining the responsiveness of log value to changes in wood characteristics. The elasticity of the conversion return, because of changes in log attributes could be complementary information for ranking trees in breeding programs.

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