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Property Modeling of Changbai Larch Veneers in Relation to Stand and Tree Variables

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Abstract. The key objective of this work was to investigate the properties of Changbai larch (*Larix olgensis* Henry) veneers in relation to stand and tree variables using both linear regression (LR) and linear mixed effects (LME) models. Veneer population dataset was from China with 36 trees of four larch stands crosscut into six segments each along vertical tree stem. The results showed that the veneer modulus of elasticity (MOE) from the first stand is highest due to the lightest thinning. Tree diameter at breast height (DBH), taper and diameter of branches were closely related. The DBH, tree height and branch height exhibited certain degrees of association with either veneer MOE or ultrasonic propagation time (UPT), but not density. Both veneer MOE and UPT exhibited a polynomial pattern along the tree stem. There was a clear descending trend in veneer density from the bottom stem to the top stem. Among all of stand and tree variables, the stem position was found to be the only significant variable affecting veneer density. As a result of combined effect of veneer UPT and density, the highest veneer MOE appeared to be situated between the second and third stem from the butt. Both the LME model and LR model demonstrated a clear similarity with regard to parameter estimates; however, the overall standard error and *p*-value from the LME models were smaller than those from the LR models, indicating that the LME model was more effective for the tree-specific analysis. After adjusting confounders including the stem position, the tree height exhibited no association with veneer MOE. This result was not available based on the standard LR analysis, indicating that the stem position has much stronger effect, in either linear or polynomial forms, on veneer MOE than the tree height. New statistical analysis methods allow us obtain additional insights of veneer properties and thus increase the value return from the available resource.

Keywords: *Changbai larch, DBH, density, growth characteristics, MOE, stand, tree, property, veneer, statistical model.*

INTRODUCTION

Forest resources are traditionally characterized through tests on clear wood and/or full size lumber (Cave and Walker 1994; Cown et al 1999; Burdon et al 2001; Liu 2004; Tong et al 2009). To date, tremendous work has been done regarding the effect of the tree growth rate on wood structure, physical and mechanical properties for various species, particularly short-rotation plantation, utilized for solid wood and pulping (Beaudoin et al 1992; Koubaa et al 1998; Li 2001; DeBell et al 2002; Zhang et al 2003; Zhang et al 2004; Deresse et al 2003; Sun and Pang 2005; Fujimoto et al 2006; He et al 2009; Wang et al 2010; Ishiguri et al 2011 a and b).

Changbai larch (*Larix olgensis* Henry) is one of the most important commercial plantation species in the northern part of China. This species has a high growth rate and high survival rate due to its strong resistance to pests, diseases, and inclement weather (Huang et al 2012 a). With an increasing volume of plantations reaching a target rotation age, this species has become one of the major fiber stocks in China. Its logs are generally very knotty, which could affect the appearance grades and some mechanical properties of end products, so pulp has been the predominant industrial application for this species (Li 2001; Sun and Pang 2005; Zhang et al 2004), followed by lumber (He et al 2009). But so far its utilization has been limited to solid wood, pulping, and paper products.

Veneer is a basic element for manufacturing plywood, laminated veneer lumber (LVL) and parallel strand lumber (PSL). Compared to dimension lumber, those veneer products have higher and more uniform stiffness and strength, greater dimension/dimensional stability and minimum defects (Wang and Dai 2001; Wang and Dai 2006). The key advantage of those products is that their performance is not necessarily limited by wood properties. They offer opportunities to convert low-value plantation logs to higher value next generation building products. However, so far only the properties of white spruce (*Picea glauca*) and hem-fir veneer and LVL have been studied from logs sampled from different stands (Knudson et al 2006; Wang et al 2010; Wang and Dai 2013). While growth characteristics of this larch species have been well documented (Li 2001; Sun and Pang 2005; Zhang et al 2004; He et al 2009), little is known about its veneer properties in relation to its site, stand management and tree growth (Huang et al 2012 a and b), let alone the modeling of veneer properties with regard to stand and tree variables.

The key properties of Changbai larch veneer, such as density and modulus of elasticity (MOE), may be related to many factors, including stand variables and tree characteristics such as diameter at breast height (DBH) and stem position, and so on. Research in this area is new and existing conclusions in the limited literature are typically based on simple statistical analysis, such as correlation analysis and simple linear regressions, without using data fully and without considering covariate adjustments (Huang et al 2012 a and b). To maximize the value return from this larch resource, a national research program was recently initiated to characterize larch plantation through veneering with regard to stand density, growth rate, and stem position to determine its suitability for veneer products such as plywood and LVL. Veneer population dataset was from China with 36 trees of four larch stands crosscut into six segments each along the vertical stem (tree height). As part of the initiative, the key objective of this work was to investigate the properties of larch veneers in relation to stand and tree variables using both linear regression (LR) and linear mixed effects (LME) models. In particular, the use of LME models for such data has not been reported. Those models can fully utilize all data available and incorporate spatial correlation in the data and thus could lead to more efficient statistical inference as well as new interesting findings.

MATERIALS AND METHODS

Tree sampling

Sample trees were obtained from Mengjiagang Forestry Center, Jiamusi, Heilongjiang province, China in East Asian continental monsoon climate zone. Four typical stands were selected with varying initial spacing (or density), final density, and stand management practices. Nine representative trees were systematically selected from each stand, three each from large (30 cm), medium (25 cm) and small (20 cm) DBH (diameter at breast height, breast height is defined as 1.3 meter from the ground level) classes, respectively (Huang et al 2012a). They were harvested, trimmed, and bucked. After felling, main tree variables, such as the DBH, age (AGE), tree height (TH), branch height (BH), crown width in the east-west direction (CWEW), crown width in the south-north direction (CWSN), and mean diameter of the five biggest branches (MD5BB), were recorded for each tree. Tree taper (TAPER) was calculated as individual tree height over its diameter difference at the two ends (with bark). For the four stands, although the initial stand density was systematically planned from 3,000 to 6,000 trees/hectare, the final density differed after three times of pre-commercial thinning and two times of commercial thinning due to the variation of thinning history and intensity. To cope with the variation of initial stand density and final stand density, the term “relative thinning intensity (RTI)” was introduced to quantify the effect of stand management and silvicultural practices on resulting veneer properties (Huang et al. 2012a).

$$\mathrm{RTI} = \frac{\text{Initial stand density - Final stand density}}{\text{Initial stand density}} \times 100\ (\%) \qquad [1]$$

Table 1 shows the main characteristics of the 9 sample trees from each of the four stands. As shown in Fig. 1, each tree was bucked into 6 segments with a mark from butt to top (crown) along the entire stem to indicate its stem position. Among those, the first segment (1300 mm from the butt) was right on the breast height for basic density measurement and veneer processing. Then, the 5 consecutive segments from 2 to 6 were cross cut with a length of 2500 mm. After that, all segments were transported to a pilot plant with each segment (from 2 to 6) being further cross cut to obtain five disks, starting from the bottom and labeled A to E for determining various wood characteristics. Among them, the section E (1250 mm long) was used for veneering.

Veneer processing

Each 1250 mm long section E (bolt) from segments 1-6 was transported to a plywood mill for veneer processing. The target veneer thickness was 2.6 mm (about 1/10 inch). The details of bolt conditioning, veneer peeling, clipping and drying were given in one early publication (Huang et al. 2012a). Veneer population, totalling 2291 sheets, was from all 36 trees crosscut into six segments each along the vertical stem (tree height). Each dry veneer sheet was marked with regard to stand, tree, stem position (or number from 1 to 6) and radial position from bark to pith. Then each sheet was nondestructively tested by Metriguard 2800 veneer tester (Metriguard Inc. 2012), which yields ultrasonic propagation time (UPT), density, or dynamic modulus of elasticity (MOE). Note that the veneer dynamic MOE is computed as follows,

$$\mathrm{MOE} = \rho \times \left(\frac{\mathrm{L}}{\mathrm{UPT}}\right)^2 \qquad [2]$$

where ρ is veneer density and L is the span for the UPT measurement. The moisture content and temperature compensation was automatically performed by the tester.

Statistical data analysis

For statistical analysis, two approaches were considered: 1) tree-level analysis; and 2) tree-specific analysis. For tree-level analysis, the focus was placed on data at tree level by averaging over the six repeated measurements of each veneer property variable along each tree stem. For tree-specific analysis, both the within-tree repeated measurement data and the between-tree data were modeled. This approach used more information and thus should be more powerful. The regression based analyses on both approaches were performed and the results were compared. In regression analyses, one of the key veneer property variables, namely UPT, density and MOE, was chosen as a dependent variable (or response) whereas the other variables (called covariates) were used to explain the variation of the dependent variable.

For each of the two approaches, an exploratory data analysis was conducted first followed by confirmatory analysis. The former is detective to visualize data pattern whereas the latter is judicial to weigh evidence in data for or against hypotheses. One particular purpose of exploratory data analysis is to detect outliers, either too large or too small relative to the rest of data. One drawback of the tree-level analysis is that it is possible that the aggregation masks certain outliers because of the averaging. In the exploratory analysis, some suspicious "outliers" were identified followed by a sensitivity analysis. The sensitivity analysis with reduced data, i.e. after removing "outliers", would have numerical difference with the original data based analysis, also, certain effect tests would change from significant to insignificant and vice versa, but it would not impact the general conclusion. The confirmatory analysis was comprised of univariate analysis and multiple analysis using linear regression method. In the univariate analysis, the association of an independent variable such as DBH with each of the dependent veneer property variables, independent of all other independent variables. While in the multiple regression analysis, the impact of other independent variables on the study relationship between the study independent variable and the study dependent variable was explored.

Tree-level analysis – a linear regression (LR) model

In the univariate analysis, for certain independent variables, models were built to include non-linear terms, for example, DBH^2. However, in all cases, the mathematical expression was similar. A vector was used to represent all included independent variables (or covariates) and associated terms (e.g. nonlinear term). Thus, a unified expression was established for both univariate and multiple analyses.

Specifically, for i^{th} individual tree, we have

$$y_i = x_i^T \beta + e_i \qquad e_i \sim N\ (0,\ \sigma^2)\ ,\ i = 1, 2, \ldots., n \qquad [3]$$

Where y_i is the study response and x_i is the vector for covariates /terms and e_i is the error term which is assumed to follow a normal distribution with zero mean and variance σ^2**.** Note that n = 36 for this study.

As an example, in the analyses of veneer MOE with continuous covariate, for example, stand RTI, the univariate analysis uses a linear regression which has the following form

$$y_i = \beta_0 + \beta_1 x_i + e_i \qquad e_i \sim N\ (0,\ \sigma^2)\ , \quad i = 1, 2, \ldots., n \qquad [4]$$

Where y_i is the observation of veneer MOE for tree i, β_0 is the intercept term and β_1 is the coefficient for x_i, the covariate RTI in this case. The estimated effect of each covariate on the response was tested to see if the association is statistically significant.

For a multiple regression analysis of this relationship, the model might include another covariate, for example, tree DBH, to account for the confounding effect, which has the following form

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 CF_i + e_i \qquad e_i \sim N(0, \sigma^2), \quad i = 1, 2, \ldots, n \qquad [5]$$

Where β_2 is the coefficient for CF_i, the confounder, DBH in this case. A forward stepwise model selection procedure was conducted. The selection criteria was that the new model, i.e., the one with a new covariate added, must have a smaller AIC (Akaike Information Criteria) comparing to the model without this new covariate. The model growing was stopped when no covariate can be added to improve model fitting. AIC was defined as

$$AIC = -2 \ln L + 2 * k \qquad [6]$$

Where k is the number of parameters in the statistical model, and L is the likelihood function. Finally, model diagnosis was also performed to verify if it departures from the model assumptions using QQplot and residual plot. To better display the results, we rescaled RTI, AGE, DBH, TH, BH and MD5BB by dividing their original measurements by 10. We focused on the estimation of β_1 as it reflects the association between the response and the covariate. Both the estimates from [4] and [5] were tabulated, denoted as unadjusted estimate and adjusted estimate.

Tree-specific analysis – a linear mixed effect (LME) model

This analysis mainly dealt with the stem-position specific veneer properties. The six measurements along the tree stem formed spatial data or clustered data, which are not independent since they are the measurements from the same tree. Thus, the standard regression analysis was not suitable. Thus, a linear mixed-effects (LME) model was used to analyze such clustered data, in which the random effects in the model incorporate the correlation among the clustered data within a tree, such that

Let $y_i = (y_{i1,} y_{i2}, \ldots, y_{ini})$ be the n_i clustered measurements of the response variable on individual tree i, i = 1, …, n. A general LME model can be written as

$$y_i = \beta x_i + Z_i b_i + e_i \qquad i = 1, \ldots, n,$$

$$b_i \sim N(0, D), \quad e_i \sim N(0, R_i) \qquad [7]$$

Where $\beta = (\beta_1, \ldots, \beta_p)^T$ is a $p \times 1$ vector of fixed effects; $b_i = (b_{i1,} \ldots, b_{iq})^T$ is a $q \times 1$ vector of random effects; the $n_i \times p$ matrix X_i and the $n_i \times q$ matrix Z_i are the design matrices which may contain predictors; $e_i = (e_{i1}, \ldots, e_{ini})^T$ represents random errors of the repeated measurements within individual i; D is a $q \times q$ covariance matrix of the random effects, and R_i is a $n_i \times n_i$ covariance matrix of the within-individual errors.

In LME model [7], the fixed effects β is population-level parameters and is the same for all individuals, as in a linear regression model, while the random effects b_i are individual-level parameters representing individual variations from population-level parameters. Namely, the random effects b_i measure between-individual variation, and the random errors e_i measure within-individual variation. Since each individual shares the same random effects, the multiple measurements within each individual are correlated. We assume that b_i and e_i are independent.

For the tree-specific analysis, an LME model for clustered data can be obtained from the corresponding linear regression model by introducing random effects in the model to account for between-tree variation and within-tree correlation. For example, when using LME to model the continuous veneer MOE to assess the association with the stand RTI, in the univariate analysis we fitted the following model for tree i:

$$y_i = \beta_0 + \beta_1 x_i + b_i + e_i \qquad i = 1, 2, \ldots, n,$$

$$b_i \sim N\,(0, \sigma_B^2), \quad e_i | b_i \sim N\,(0, \sigma_W^2 I_{ni \times ni}) \qquad [8]$$

Where y_i and x_i are the $n_i \times 1$ vector of veneer MOE, and stand RTI, respectively; $\beta = (\beta_0, \beta_1)$ are the fixed effects; b_i is the random effect; σ_B^2 and σ_W^2 are the between-tree and within-tree variances, respectively.

In the multiple analysis, the model has the following form

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 CF_i + b_i + e_i \qquad i = 1, 2, \ldots, n,$$

$$b_i \sim N\,(0, \sigma_B^2), \quad e_i | b_i \sim N\,(0, \sigma_W^2 I_{ni \times ni}) \qquad [9]$$

Where CF_i is the controlled confounder, and β_2 is the coefficient for CF_i. Note that we always include the random intercept b_i to account for the tree to tree variation, and use AIC as a model fitting criterion.

RESULTS AND DISCUSSION

Table 2 summarizes the mean measurement results for total 12 variables, 3 for veneer properties, 2 for stands and 7 for trees. For both tree-level analysis and tree-specific analysis, an explorative data analysis was performed first, followed by a confirmatory analysis.

Tree-level analysis

For the explorative data analysis, the pair-wise relationship between a response and a covariate was plotted to determine what form (linear, quadratic, or other types) of a covariate could be used to model the relationship. Meanwhile, those plots helped visualize outliers in the data.

As an example, Figure 2 shows the scatter plot regarding how veneer MOE is affected by tree DBH. There was a possible nonlinear relationship with veneer MOE peaked at certain DBH (about 25 cm). As a result, in the analysis for veneer MOE, two models were used to evaluate the association between veneer MOE and tree DBH, one with a linear term only and the other with both linear term and quadratic term, i.e., a polynomial relationship.

Figure 3 is the boxplot showing how veneer MOE changes with stand RTI. On average, the stand 1 with an RTI of 80.67% yielded the highest veneer MOE. Also this plot shows that there are a few abnormal observations in stand 3 (RTI = 93.9). There was no significant difference in veneer MOE among the other three stands (2, 3 and 4). Among the four managed larch stands, stand 1 with the lowest RTI had the highest veneer MOE due to the lightest thinning. Thus, the RTI could be potentially used to describe the complexity of stand management for this species with varying initial density and final density, and help characterize the effect of stand management on veneer properties.

The relationships among the covariates were further explored. Figure 4 shows the pair wise correlation among the three tree covariates: DBH, TAPER and MD5BB, with a positive correlation coefficient larger than 0.8. The larger the DBH, the greater the taper and diameter of branches. The high correlation would not affect univariate analyses but multiple analyses. To avoid co-linearity, the cases when any two of those three covariates in the same model were eliminated.

For the confirmatory analysis, Tables 3 to 5 summarize the results for the univariate and multiple regression for veneer UPT, density and MOE, respectively. The estimate of β_1, its standard error (SEE), *p*-value and R^2 were given. The p-value is testing if $\beta_1$differs from zero (zero for non-relationship). When the p-value is smaller than a commonly used threshold 0.05, it is concluded that the predictor is significantly associated with the response.

Based on Table 3, compared to the stand 1, the stand 2 had significantly larger UPT. Veneer UPT was significantly affected by the tree DBH. The east-west crown width tended to associate with veneer UPT but no confounders could be added to control this effect. Based on Table 4, no significant association was found between veneer density and listed stand and tree covariates.

As shown in Table 5, the RTI started to show statistical significance after controlling the listed confounders, DBH, DBH^2, BH and CWEW. Every 10% increase in thinning, the expected reduction of veneer MOE was about 0.52 GPa. Stand indicator (1 to 4) exhibited marginal significant association with veneer MOE ($p<0.1$) after controlling the included confounders DBH, DBH^2 and BH. If those confounders hold constant, comparing to “stand 1”, all the other three stands have about 0.8 GPa lower in mean veneer MOE. DBH and DBH^2 were tested to be significantly associated with veneer MOE. Branch height (BH) started to show significant association with veneer MOE in the multiple regression model but not in the univariate model. Tree height (TH) had marginal association with veneer MOE and all other covariates did not seem to correlate with veneer MOE.

Tree-specific analysis

For the explorative data analysis, Figure 5 shows the box plots regarding how veneer MOE changes with the stem position for each stand. The horizontal line is the overall median of veneer

MOE, i.e. 12.89 GPa. The stand 1's MOE median values from each stem position are mostly above this line, whereas the stand 2's MOE drops slightly, and the stands 3 and 4 show the lowest MOE. In general, the stem positions 2 and 3 had relatively higher veneer MOE compared to other 4 stem positions, exhibiting a polynomial pattern. However, this pattern was slightly different from stand to stand. For stand 1, the stem positions 1-4 had higher veneer MOE than stem positions 5-6. For stand 2, the stem positions 1-3 had relatively higher veneer MOE. For stand 3 and stand 4, the stem positions 2 and 3 had higher veneer MOE than the other 4. The results demonstrated that the stiffest veneer was generally from the second to the third stem, which is more suitable for manufacturing structural veneer products such as LVL with a higher grade outturn. The first stem had the largest diameter but not necessary the highest veneer MOE, which is more suitable for manufacturing non-structural veneer products such as plywood with a higher yield. Starting from the fourth stem upward, the veneer MOE tended to decrease. Due to their smaller diameter, those stems may be more suitable for manufacturing non-veneer based composites such as medium density fiberboard (MDF) and particleboard or for chipping and lumber products. Further, the plots also displayed certain individual data points which are beyond the normal range of the data, which could be the outliers.

Figure 6 shows the trend plot regarding how veneer properties change with stem position for each of the four stands. Both veneer MOE and UPT exhibited a polynomial pattern from the bottom stem 1 to the top stem 6. The stem positions 2 and 3 generally had the higher veneer MOE except the stand 2. The trend of veneer UPT was consistent among the four stands with a typical "U" shape. The stem positions 3 and 4 yielded the lowest UPT. The veneer UPT is mainly affected by wood grain deviation, knots, knot holes and decay, and so on. The reason why the stem positions 1 and 2 had a higher UPT could be mainly due to their higher growth rate of juvenile wood. The results indicated that the stem positions 3 and 4 could have the smallest grain deviation. As far as the veneer density is concerned, there was a clear descending trend from the bottom stem to the top stem. As a result of combined effect of veneer UPT and density, the higher veneer MOE appeared to be in the 2^{nd} to 3^{rd} stem position.

For the confirmatory analysis, Table 6 shows the LME modeling results for veneer UPT using both univariate and multiple regression methods. There was a strong signal that veneer UPT is closely associated with the stem position in a polynomial form. Also veneer UPT is closely associated with crown width in the east-west orientation and stem position (p = 0.03). Similarly, Table 7 shows the LME modeling results for veneer density. Expect the stem position, there was no significant relationship between veneer density and any of the stand and tree variables.

Table 8 shows the LME modeling results for veneer MOE using both univariate and multiple regression methods. Compared to the linear regression (LR) model of veneer MOE (Table 5), there was a clear similarity with regard to parameter estimates; however, the overall standard error (SEE) and p-value from the LME models were smaller than those from the LR models, indicating that the LME model was more effective. The gain in model efficiency could make some hypothesis tests becoming significant, for example, the stand 1 had significantly higher veneer MOE than the stands 3 or 4. Tree DBH also had some effect on veneer MOE in a polynomial form. After adjusting confounders including the stem position, the tree height (TH) exhibited no association with veneer MOE. This result was not available from the LR analysis, indicating that the stem position has much stronger effect than the tree height on veneer MOE in either linear or polynomial forms. Stem position was a better veneer MOE predictor than tree height.

CONCLUSIONS

Both tree-level and tree-specific analyses were conducted for Changbai larch veneer properties from four managed stands using univariate and multiple linear regression (LR) and linear mixed-effects (LME) models. The results demonstrated that the stand 1's veneer MOE is highest due to the lightest thinning. Tree DBH, taper and diameter of branches were closely related. The larger the tree DBH, the greater the taper and diameter of branches. Tree DBH, height and branch height were shown certain degrees of association with either veneer MOE or UPT, but not density. The DBH's association was found to be most consistent from both univariate and multiple analyses. Both veneer MOE and UPT exhibited a polynomial pattern from the bottom stem to the top stem with positions 2 and 3 generally having higher veneer MOE. The trend of veneer UPT was consistent among the four stands, displaying a polynomial pattern with stem positions, a typical "U" shape. The reason why the low stem positions (1 and 2) had a higher UPT could be mainly due to their higher growth rate of juvenile wood. The middle stem positions (3 and 4) yielded the lowest UPT, indicating potential smallest grain deviation. There was a clear descending trend in veneer density from the bottom stem position to the top stem position. Expect the stem position, there was no significant relationship between veneer density and any of the stand and tree variables. As a result of combined effect of veneer UPT and density, the highest veneer MOE appeared to be in the 2^{nd} to 3^{rd} stem position.

Both LME model and LR model showed a clear similarity with regard to parameter estimates; however, the overall standard error and p-value from the LME model were smaller than those from the LR model, indicating that the LME model was more effective in the tree-specific analysis. After adjusting confounders including stem position, the tree height exhibited no association with veneer MOE. This result was not available from the standard LR analysis, indicating that the stem position has much stronger effect than the tree height on veneer MOE in either linear or polynomial forms. New statistical methods allow us to obtain additional insights of veneer property and thus allow us to increase value return from the resource available based on new findings. More elaborate statistical analyses will be conducted to further explore the larch datasets including multivariate mixed-effects models, missing data and measurement error methods.

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Table 1. Sampling schemes and stand characteristics of larch trees

Stand no.	Initial spacing (trees/ ha.)	Final density (trees/ ha.)	RTI (%)	Site index		Mean DBH (cm)	Number of trees
				Age (year)	Mean tree height (m)		
1	3000	580	80.7	46	21.8 (1.59)*	24.5 (5.58)	1-9
2	4000	487	87.8	53	21.5 (1.06)	23.2 (4.54)	10-18
3	5000	305	93.9	53	22.3 (1.05)	25.0 (3.64)	19-27
4	6000	200	96.7	49	22.0 (1.03)	26.8 (4.80)	28-36

* Standard deviation

Table 2. The measurement results of total 12 veneer, stand and tree variables

Variable			Unit	Mean	Std. Dev.
Category	Type	Name			
Veneer	Dependent (or response)	MOE	GPa	12.9	0.96
		UPT	μs	201.4	6.96
		DENSITY	Kg/m^3	526.8	35.01
Stand	Independent (or covariate)	RTI	%	89.8	6.24
		AGE	Year	50.3	2.99
Tree	Independent (or covariate)	DBH	cm	25.00	4.76
		TH	m	21.9	1.40
		BH	m	11.4	2.68
		CWEW	m	4.2	1.04
		CWSN	m	4.3	1.08
		TAPER	%	2.2	0.44
		MD5BB	cm	43.5	9.67

Table 3. Univariate and multiple regression analysis for veneer UPT

	Univariate				Multiple				
	β_1	SEE*	*p*	R^2	β_1	SEE*	*p*	R^2	Confounders
RTI	1.96	1.88	0.30	0.03	-0.24	2.08	0.91	0.20	DBH, AGE
AGE	5.55	3.88	0.16	0.06	6.07	3.62	0.10	0.20	DBH
STAND (2 vs. 1)	5.72	3.27	0.09	0.09	6.11	3.06	0.05	0.23	
STAND (3 vs. 1)	3.13	3.27	0.35	0.09	2.83	3.05	0.36	0.23	DBH
STAND (4 vs. 1)	4.04	3.27	0.22	0.09	2.79	3.10	0.37	0.23	
DBH	5.36	2.33	0.03	0.13	5.58	2.28	0.02	0.20	AGE
TH	9.38	8.39	0.27	0.04	3.42	8.74	0.70	0.12	CWEW
BH	0.98	4.44	0.83	0.00	2.27	4.16	0.59	0.21	DBH,AGE
CWEW	2.31	1.07	0.04	0.12	2.31	1.07	0.04	0.12	
CWSN	2.04	1.05	0.06	0.10	2.04	1.05	0.06	0.10	
TAPER	3.98	2.60	0.14	0.06	0.98	3.27	0.77	0.12	CWEW
MD5BB	1.28	1.21	0.30	0.03	-0.08	1.39	0.96	0.12	CWEW

*Standard error of estimate

Table 4. Univariate and multiple regression analysis for veneer density

	Univariate				Multiple				
	β_1	SEE*	*p*	R^2	β_1	SEE*	*p*	R^2	Confounders
RTI	-6.05	9.57	0.53	0.01	-9.24	9.71	0.35	0.13	TH,BH
AGE	7.74	20.04	0.70	0.00	8.36	19.58	0.67	0.08	RTI,TH
STAND (2 vs. 1)	11.05	16.9	0.52	0.04	9.32	16.64	0.58	0.10	
STAND (3 vs. 1)	-4.63	16.9	0.79	0.04	-2.22	16.68	0.89	0.10	TH
STAND (4 vs. 1)	-7.37	16.9	0.67	0.04	-7.51	16.6	0.65	0.10	
DBH	-19.4	12.18	0.12	0.07	-19.4	12.18	0.12	0.07	
TH	-67.89	41.39	0.11	0.07	-67.89	41.39	0.11	0.07	
BH	-27.5	21.88	0.22	0.04	-27.14	21.41	0.21	0.11	DBH
CWEW	-4.26	5.71	0.46	0.02	-1.01	6.06	0.87	0.07	TH
CWSN	-0.85	5.56	0.88	0.00	8.19	7.03	0.25	0.11	DBH
TAPER	-2.8	13.54	0.84	0.00	15.16	16.21	0.36	0.10	TH
MD5BB	-5.64	6.13	0.36	0.02	-5.64	6.13	0.36	0.02	

*Standard error of estimate

Table 5. Univariate and multiple regression analysis for veneer MOE

	Univariate				Multiple				
	β_1	**SEE***	***p***	R^2	β_1	**SEE***	***p***	R^2	**Confounders**
RTI	-0.23	0.26	0.38	0.02	-0.52	0.24	0.04	0.42	DBH^2, DBH,BH, CWEW
AGE	-0.17	0.55	0.76	0.00	-0.42	0.51	0.42	0.24	DBH, BH
STAND (2 vs. 1)	-0.16	0.47	0.73	0.02	-0.78	0.42	0.07	0.41	DBH^2,DBH,BH
STAND (3 vs. 1)	-0.24	0.47	0.61	0.02	-0.76	0.42	0.08	0.41	
STAND (4 vs. 1)	-0.41	0.47	0.39	0.02	-0.79	0.43	0.08	0.41	
DBH (model 1)	-0.83	0.32	0.01	0.17	-0.83	0.31	0.01	0.23	BH
DBH (model 2)	6.63	3.85	0.09	0.25	11.11	4.01	0.01	0.42	BH, RTI, CWEW
DBH^2 (model2)	-1.46	0.75	0.06	0.25	-2.25	0.76	0.01	0.42	
TH	-2.21	1.12	0.06	0.10	-2.21	1.12	0.06	0.10	
BH	-0.88	0.6	0.15	0.06	-1.38	0.54	0.02	0.42	DBH^2,DBH,RTI,CWEW
CWEW	-0.25	0.15	0.1	0.08	-0.26	0.18	0.15	0.42	DBH^2,DBH,BH,RTI
CWSN	-0.15	0.15	0.32	0.03	-0.07	0.19	0.71	0.39	DBH^2,DBH,BH,RTI
TAPER	-0.31	0.37	0.41	0.02	0.56	0.5	0.27	0.26	TH,CWEW,BH,RTI
MD5BB	-0.19	0.17	0.27	0.04	0.03	0.22	0.89	0.10	TH

*Standard error of estimate

Table 6. Univariate and multiple regression for repeated veneer UPT

	Univariate				Multiple				
	β_1	**SEE***	***p***	R^2	β_1	**SEE***	***p***	R^2	**Confounders**
RTI	1.81	1.92	0.34	0.02	1.78	1.76	0.32	0.32	STEM,$STEM^2$,CWEW
AGE	5.24	3.95	0.18	0.03	5.49	3.59	0.14	0.32	STEM,$STEM^2$,DBH
STAND (2 vs. 1)	5.5	3.35	0.10	0.08	5.91	2.95	0.05	0.32	
STAND (3 vs. 1)	2.98	3.33	0.37	0.08	2.51	2.92	0.4	0.32	STEM,$STEM^2$,DBH
STAND (4 vs. 1)	3.84	3.34	0.25	0.08	3.08	2.96	0.31	0.32	
DBH	5.59	2.35	0.02	0.05	5.49	3.59	0.14	0.32	$STEM^2$,DBH
TH	9.96	8.41	0.24	0.04	-13.05	11.62	0.27	0.33	$STEM^2$,DBH,AGE
BH	1.52	4.50	0.74	0.03	1.29	4.06	0.75	0.32	$STEM^2$,DBH,AGE
CWEW	2.33	1.08	0.03	0.03	2.44	1.06	0.03	0.31	$STEM^2$
CWSN	2.13	1.06	0.04	0.03	0.87	1.33	0.52	0.32	$STEM^2$,DBH
TAPER	3.88	2.65	0.14	0.03	0.72	3.17	0.82	0.32	$STEM^2$,CWEW
MD5BB	1.27	1.25	0.31	0.02	-0.46	1.34	0.74	0.34	$STEM^2$,CWEW,RTI
STEM (model 1)	-0.68	0.50	0.17	0.00	-0.76	0.51	0.14	0.04	DBH,AGE
STEM (model 2)	-17.9	1.94	<0.001	0.00	-17.82	1.95	<0.001	0.32	DBH,AGE
$STEM^2$ (model 2)	2.49	0.27	<0.001	0.00	2.47	0.28	<0.001	0.32	DBH,AGE

*Standard error of estimate

Table 7. Univariate and multiple regression for repeated veneer density

	Univariate				Multiple				
	β_1	SEE*	*p*	R^2	β_1	SEE*	*p*	R^2	Confounders
RTI	-6.96	9.56	0.47	0.04	-11.23	9.69	0.26	0.29	STEM,$STEM^2$,BH
AGE	6.30	20.12	0.75	0.04	7.54	19.55	0.70	0.29	STEM,$STEM^2$,TH
STAND (2 vs. 1)	9.55	16.95	0.57	0.12	4.29	17.03	0.80	0.29	
STAND (3 vs. 1)	-5.73	16.91	0.73	0.12	-9.82	16.26	0.55	0.29	$STEM^2$,BH
STAND (4 vs. 1)	-8.85	16.94	0.60	0.12	-16.53	17.35	0.35	0.29	
DBH	-20.38	12.14	0.09	0.05	-17.6	12.32	0.16	0.29	$STEM^2$
TH	-69.58	41.16	0.09	0.06	-64.16	41.65	0.13	0.29	$STEM^2$
BH	-26.41	22.04	0.23	0.05	-26.7	21.5	0.22	0.30	$STEM^2$,TH
CWEW	-4.62	5.68	0.42	0.03	0.09	6.01	0.99	0.29	$STEM^2$,TH
CWSN	-1.11	5.59	0.84	0.03	8.65	6.99	0.22	0.30	$STEM^2$,DBH
TAPER	-3.34	13.56	0.81	0.04	17.2	16.03	0.29	0.30	$STEM^2$,TH
MD5BB	-6.13	6.18	0.32	0.03	-3.96	6.1	0.52	0.29	$STEM^2$
STEM (model 1)	-10.69	1.70	<0.001	0.00	-10.6	1.71	<0.001	0.15	TH
STEM (model 2)	-53.94	7.30	<0.001	0.00	-53.95	7.33	<0.001	0.29	TH
$STEM^2$ (model 2)	6.25	1.03	<0.001	0.00	6.26	1.04	<0.001	0.29	TH

*Standard error of estimate

Table 8. Univariate and multiple regression analysis for repeated veneer MOE

	Univariate				Multiple				
	β_1	SEE*	*p*	R^2	β_1	SEE*	*p*	R^2	Confounders
RTI	-0.25	0.27	0.35	0.00	-0.54	0.23	0.02	0.18	STEM,DBH^2,$STEM^2$,DBH,BH,CWEW
AGE	-0.19	0.56	0.73	0.00	-0.86	0.49	0.09	0.16	STEM,DBH^2,DBH,$STEM^2$,BH
STAND (2 vs. 1)	-0.18	0.48	0.7	0.01	-0.74	0.4	0.07	0.18	
STAND (3 vs. 1)	-0.26	0.48	0.58	0.01	-0.78	0.4	0.05	0.18	DBH^2,DBH,BH,$STEM^2$
STAND (4 vs. 1)	-0.44	0.48	0.36	0.01	-0.81	0.4	0.05	0.18	
DBH (model 1)	-0.87	0.32	0.01	0.03	-0.81	0.31	0.01	0.13	$STEM^2$,BH
DBH (model 2)	6.44	3.93	0.10	0.06	11.78	3.88	<0.001	0.18	$STEM^2$,BH,RTI,CWEW
DBH^2 (model 2)	-1.43	0.77	0.06	0.06	-2.37	0.74	<0.001	0.18	
TH	-2.28	1.13	0.04	0.03	0.24	1.46	0.87	0.18	$STEM^2$,DBH^2,DBH,BH,RTI,CWEW
BH	-0.88	0.61	0.15	0.02	-1.37	0.52	0.01	0.18	DBH^2,$STEM^2$,DBH,RTI,CWEW
CWEW	-0.26	0.15	0.09	0.01	-0.27	0.17	0.12	0.18	$STEM^2$,DBH^2,DBH,BH,RTI
CWSN	-0.16	0.15	0.28	0.00	0.13	0.2	0.52	0.18	DBH^2,$STEM^2$,DBH,BH,RTI,CWEW
TAPER	-0.32	0.38	0.39	0.00	0.58	0.48	0.23	0.14	$STEM^2$,TH,CWEW,BH,RTI
MD5BB	-0.20	0.17	0.24	0.00	0.17	0.21	0.41	0.16	$STEM^2$,TH,RTI,BH
STEM (model 1)	-0.16	0.05	<0.001	0.00	-0.16	0.05	<0.001	0.16	DBH^2,DBH,BH,RTI,CWEW
STEM (model 2)	0.31	0.22	0.16	0.00	0.30	0.22	0.18	0.18	DBH^2,DBH,BH,RTI,CWEW
$STEM^2$ (model 2)	-0.07	0.03	0.03	0.00	-0.07	0.03	0.04	0.18	DBH^2,DBH,BH,RTI,CWEW

*Standard error of estimate

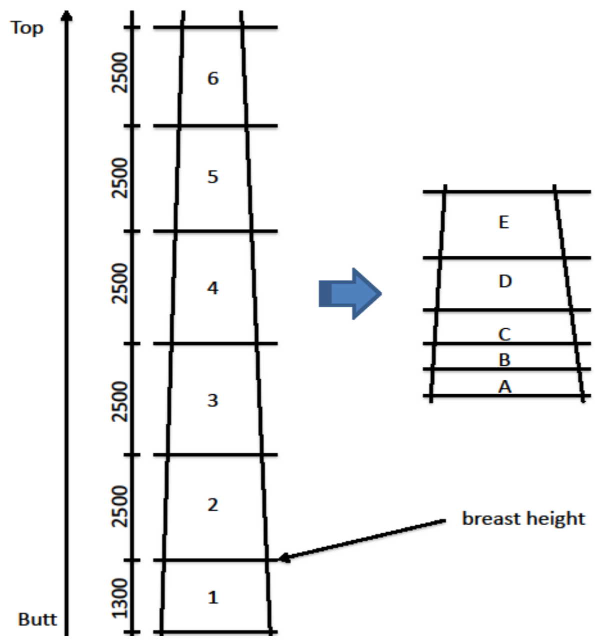

Figure 1: Sampling trees cross-cut for veneering

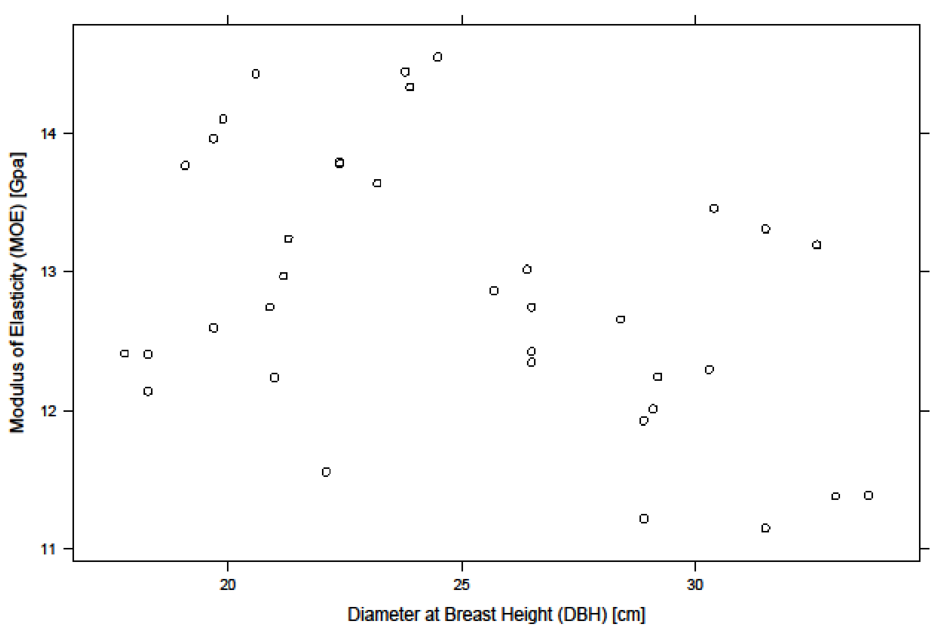

Figure 2: Scatter plot of veneer MOE in relation to tree DBH

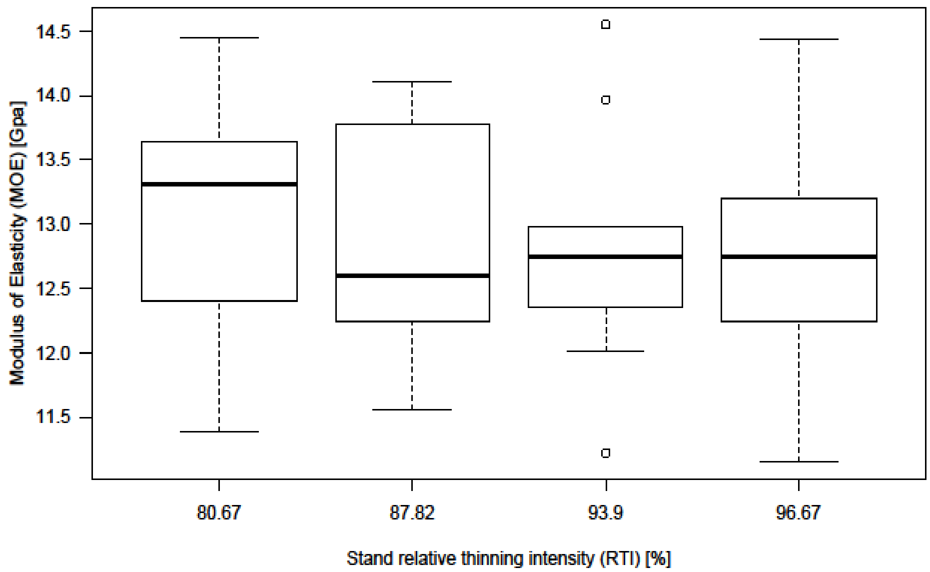

Figure 3: Effect of stand relative thinning intensity on veneer MOE

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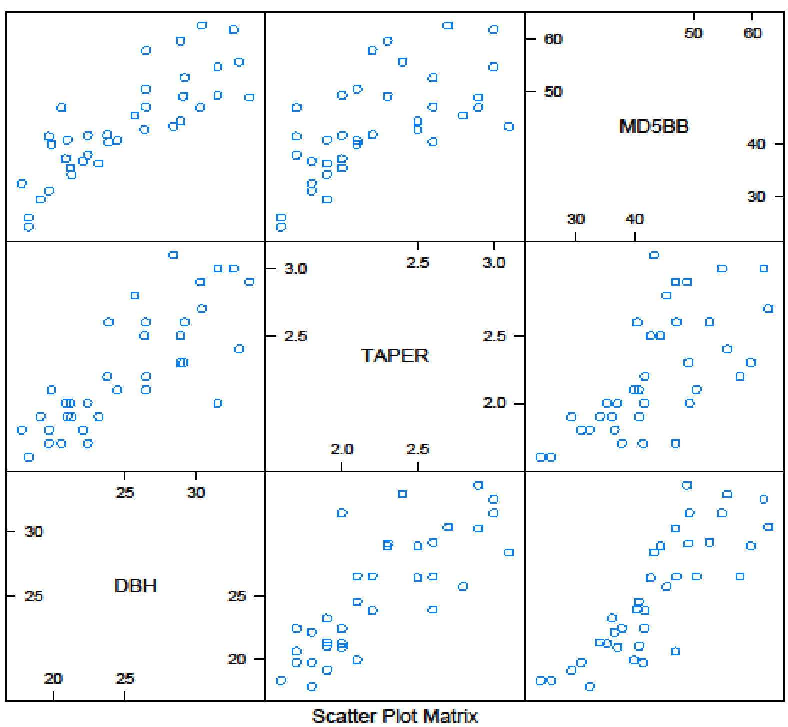

Figure 4: Scatter plots of the three tree covariates (DBH, TAPER and MD5BB)

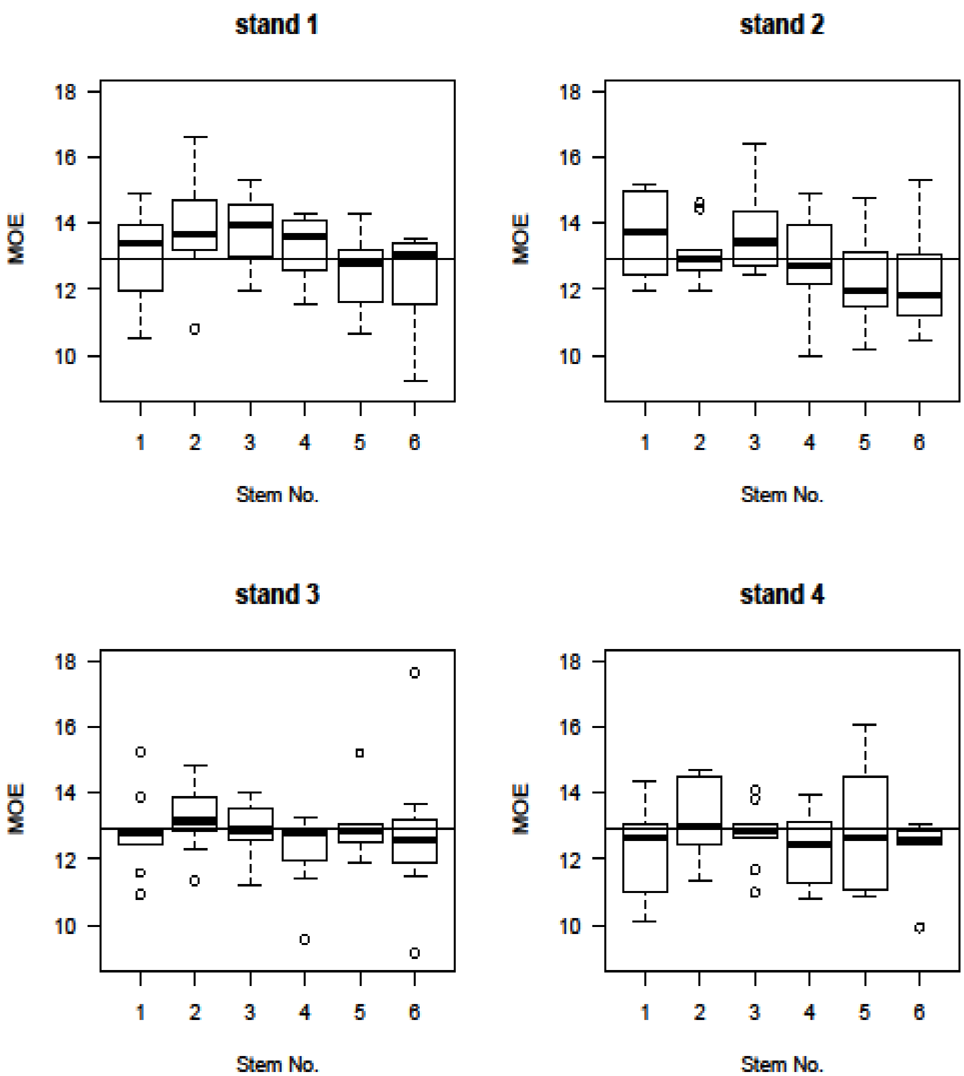

Figure 5: Effect of the tree stem position on veneer MOE with regard to stand

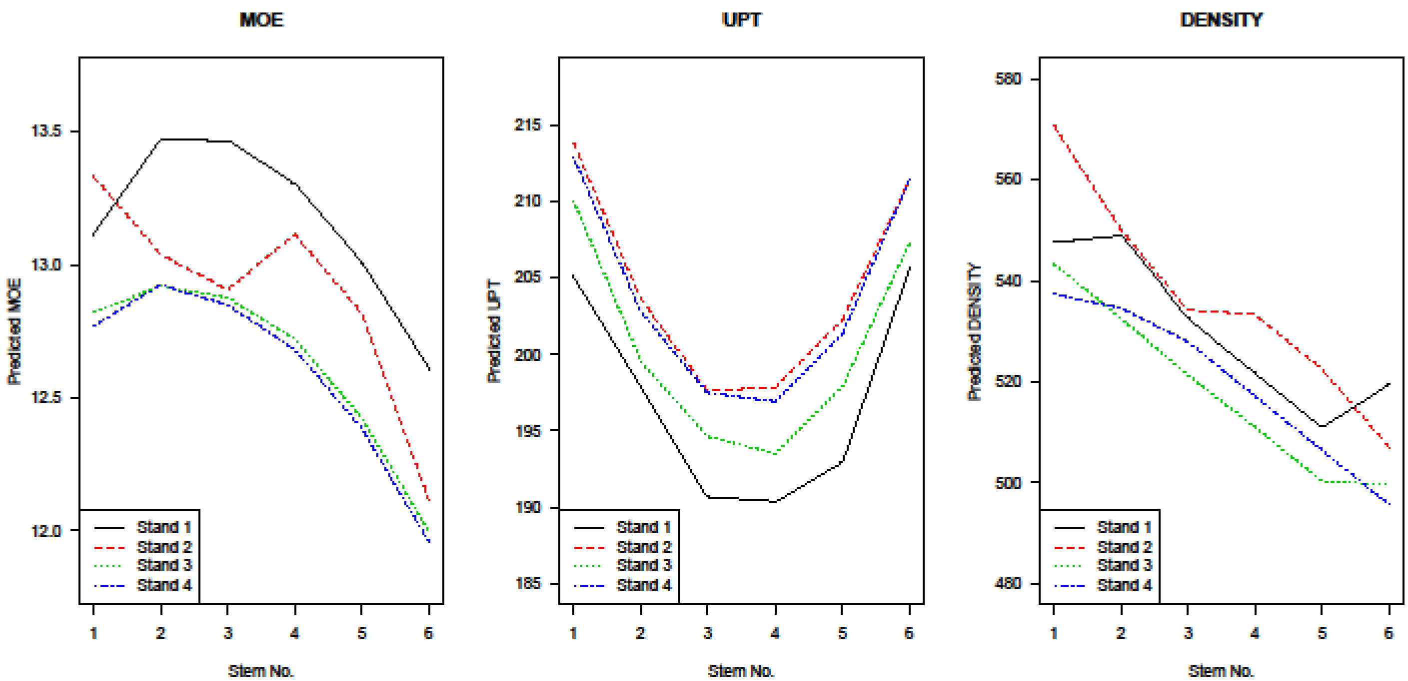

Figure 6: Change of veneer properties with regard to the stand and tree stem position