Deriving Wood Quality Properties Through Their Links With Tree And Stand Attributes

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Abstract

One of the important Canadian Wood Fibre Centre's mandates is to develop methods to facilitate the flow of information on the wood quality and quantity along the chain of forest values. Among its research projects, one entitled Enhanced Forest Inventory aims to produce tools to map the wood attributes in terms of physico-mechanical properties by using prediction models based on the attributes of the forest tree and stand. The main inputs of these models come from non-destructive measurements on standing trees (acoustic probe, resistograph, terrestrial lidar) and from spatial data (aerial lidar). Among the obtained results, the correlations are significant between acoustic velocity, drill resistance, and tree and stand attributes. These results open the prospect of using the data of non destructive measurements such as acoustic probe and resistograph as complementary input with tree and stand attributes (dbh, crown, and competition index) for prescribing the intensity of thinning to a desired level of wood density.

Key words: non-destructive measurements, tree and stand attributes, acoustic velocity, resistograph, wood density

Introduction

The forest is currently subject to diverse and growing expectations for resources (timber production, carbon sinks, biodiversity, recreation, landscape, and hunting). To date, wood sale is the main financial resource of the forest and contributes, thereby ensuring the integrity of the forest and the ecological and social functions it fulfills in North America. However, in recent years, the profitability of timber production has declined significantly. It was therefore necessary to consider more efficient silvicultural methods and more innovative timber processing. Among all the solutions considered, the tree silviculture (irregular silviculture, tree-target silviculture) appears as a way to ensure profitability while preserving the forest ecological and social issues of the forest. These diverse and high unit value woods require marketing methods highlighting their own unique qualities. These changes were implemented and led the whole wood forest chain (from producers to processors) to adapt. For answering to these changes, we proposed to produce tools to map the quantity and quality of forest wood using predictive models based on nondestructive evaluation of mechanical wood traits and on tree and stand attributes. Here we present the preliminary results of two objectives:
1.Predicting the acoustic velocity from the standing tree attributes
2.Quantifying the correlations between drill resistance profiles, acoustic velocity data, tree attributes, and inter tree competition.

Objective 1. Predicting the acoustic velocity from the standing tree attributes

Context. Theoretically, acoustic velocity is related to wood density and dynamic modulus of elasticity as following:

$$v = \sqrt{\frac{MoE}{\rho}} \qquad [1]$$

where v is the acoustic velocity (km/s), MoE is the modulus of elasticity or wood stiffness (N/m^2), and ρ is the wood density (kg/m^3). Thus, the more accurate is the measurement of v by non-destructive device ST300 (http://www.fibre-gen.com/st300.html) or by the destructive device HM200 (http://www.fibre.gen.com/hm200.html), the more promising the derivation of ρ or MoE from Eq. 1 will be. Indeed, Auty and Achim (2008) demonstrated that v and ρ can be used to predict MoE and particularly that v can be used for sorting logs in the sawmill yard. Also, Jones and Emms (2010) showed that there are strong associations between the log acoustic velocity and branch size variables, the number of branches and whorls. Obtaining the earliest possible assessment of wood quality is primordial to the efficiency and the sustainability of the wood value-chain i.e. for assessing and tracing wood properties from the standing tree to the end-product. Then, it becomes relevant to assess the reliability of v to obtain an early assessment of wood quality on logs (destructive velocity) and especially on standing tree (non-destructive velocity). In addition, as destructive velocity might be more expensive than the non-destructive velocity because it requires harvest, it is justified to quantify the gain in accuracy of the destructive velocity on logs, compared with the non-destructive velocity on trees.

Material. Non-destructive acoustic velocity was measured on 40 sugar maple (*Acer saccharinum* L.) trees and 24 yellow birch (*Betula alleghaniensis* Britton) trees sampled from sixteen 400-m^2 circular plots. Plots were distributed across two forest eco regions in New Brunswick, Canada. The measured tree attributes were stem diameter at 1.30 m (dbh), total height, and crown variables (Fig. 1). These crown variables allowed computing light crown area especially. Two types of tree defects were measured. First, the stem deformation (curvature and elbow) is quantified by the ratio depth/length. Second tree defect was recorded as either, hole, split, wound, or stump swelling and these variables were estimated by their area (width x length). Each of the 64 trees was bucked, and destructive velocity was measured on each sawlogs produced. The destructive velocity in the tree is the mean velocity in logs weighted by the log volumes; each log was assumed to be a truncated cone. Table 1 summarises the obtained data.

Table 1 Data summary: tree, stand, non-destructive velocity and destructive velocity

Variable	**Sugar maple n=40**				**Yellow birch n=24**			
	Min	**Max**	**Mean**	**Std**	**Min**	**Max**	**Mean**	**Std**
Stand basal area m^2/ha	14.00	33.00	25.18	5.86	14.00	33.00	23.96	4.94
Stand height m	17.65	24.50	21.06	2.11	17.40	21.42	18.85	1.29
Dbh cm	24.00	48.00	33.40	6.93	24.00	50.00	33.42	7.06
Crown width dm	15.333	39.67	28.47	6.01	17.67	45.33	31.91	6.03
Total crown area m^2	163.28	673.14	384.97	106.18	171.54	714.00	399.89	123.97
Light crown area m^2	130.55	646.57	342.67	116.09	155.11	638.86	327.85	113.34
Non-destructive velocity km/s	2.94	4.08	3.58	0.27	3.37	4.30	3.88	0.23
Destructive velocity km/s	3.25	4.69	4.07	0.26	3.82	4.71	4.30	0.23

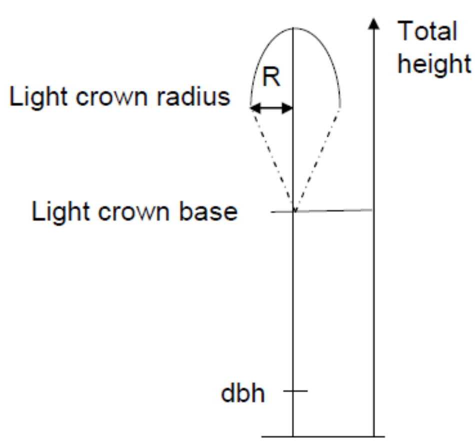

Figure 1. Tree parameters

Method. The following linear regression was used for addressing the prediction of velocity by tree attributes:

$$v_{ij} = \mu + S_j + T_{ij} + e_{ij} \qquad [2]$$

with v_{ij} acoustic velocity of tree i in plot j, μ the overall population mean, S_j the fixed effects of stand attributes, T_{ij} the fixed effects of tree i attributes in plot j, and e_{ij} random error of tree i in plot j. The mixed model procedure was used for separating the fixed effects of tree and stand attributes from the random effect.

Results and discussion. Tree species effect was significant on non-destructive and destructive velocity (Table 2). Stand attributes represented by stand basal area and stand height were not significant on both velocities and for both species (Table 3). The insignificant impact of stand attributes should be caused by the relatively narrow range of the observed stand basal and stand height. None of the considered tree defects had significant effect on both velocities and for both species (tests not shown). Apparently, this lack of correlation seems to contradict Sandoz and Lorin (1996) who advocated the use of acoustic velocity for detecting gross defects on standing trees (cavity, advanced decay or soft rot). However, in reality, this lack of correlation in our data simply means that the observed defects are not quite as advanced as the defects considered by Sandoz and Lorin (1996). It is clear that tree dbh, tree crown width, and light crown area explain significantly both velocities and for both species.

Table 2 Tree species effect on non-destructive and destructive velocity

Numerator degree of freedom=1 Denominator degree of freedom=62	Effect	F value	Pr >F
Non-destructive velocity	Tree species	12.72	0.0007
Destructive velocity* (avg. per tree)	Tree species	19.54	<0.0001

(*on sawlogs only)

Table 3 Effects of dbh, tree height, tree crown, stand basal area and stand height on non-destructive and destructive velocity

Sugar maple: numerator degree of freedom=1; denominator degree of freedom=29				
	Non-destructive velocity		**Destructive velocity**	
Effect	**F value**	**Pr >F**	**F value**	**Pr >F**
Dbh	37.96	<.0001	3.09	0.0893
Tree height	2.37	0.1343	4.17	0.0503
Crown length 1	8.69	0.0063	0.02	0.8940
Crown length 2	7.24	0.0117	0.00	0.9593
Crown width	0.92	0.3447	0.11	0.7429
Crown length 1x Crown width	11.49	0.0020	0.01	0.9090
Crown length 2x Crown width	9.95	0.0037	0.07	0.7896
Stand basal area	4.35	0.0459	0.71	0.4064
Stand heigth	0.28	0.6025	1.66	0.2083

Yellow birch: numerator degree of freedom=1; denominator degree of freedom=13				
	Non-destructive velocity		**Destructive velocity**	
Effect	**F value**	**Pr >F**	**F value**	**Pr >F**

Dbh	3.61	0.0798	5.24	0.0395
Tree height	0.70	0.4193	4.87	0.0459
Crown length 1	0.16	0.6968	0.50	0.4903
Crown length 2	7.24	0.0117	1.34	0.2683
Crown width	0.08	0.7781	0.48	0.4999
Crown length 1x Crown width	0.00	0.9449	0.28	0.6063
Crown length 2x Crown width	0.25	0.6242	1.35	0.2669
Stand basal area	0.64	0.4377	1.31	0.2728
Stand heigth	0.72	0.4127	0.99	0.3371

Objective 2.Quantifying the correlations between wood density based on drilling resistance profiles, acoustic velocity, tree attributes, and inter tree competition.

Context. In addition to the acoustic probe, the drilling resistance device provides additional option for indirect field measurement of wood properties. The literature suggests that the mean value of resistance profiles are correlated with wood density in standing trees (Isik and Li 2003, Eckard et al 2008). Thus, we proposed to build a model of cause and effect between these two types of measurements on the one hand, and the attributes of the tree and stand on the other hand.

Material. For each of the 27 sugar maple and 23 yellow birch sampled in the same forest stands of objective 1, three types of data were collected: competition, resistograph and acoustic probe. The competition data were obtained by dividing the field into six equal areas around each of the 50 trees. For each area, the measurement on the nearest competitor tree was taken and included the distance from the nearest neighbor tree and the central tree, neighbor tree dbh, neighbor tree height, central tree crown with its neighbor crown. The second type of data available is represented by resistograph data. These data were obtained for each tree by drilling the tree at breast height from bark to pit using the IML Resistograph F400. Resistance profile data contained percent amplitude measurements at each 0.1 mm increment of drilling. Basic data such as tree species, dbh, height and crown were collected also. The third type of collected data on 50 trees was the acoustic velocity data using the ST300 probe previously mentionned in objective 1.

Method. Correlations between the three types of data were quantified using the structural equation modeling (Shipley 2002). This modeling allowed verifying the following hypothesis: competition affects tree growth and thus its size; tree size affects the velocity, which subsequently affects tree resistance. The proposed model consists of four latent variables: tree size, acoustic velocity, competition, and drill resistance (Fig. 2). The Size variable is composed of tree dbh, height and crown base. The Velocity variable consists of four successive measurements performed on each tree. Competition and Resistance variables are described below.

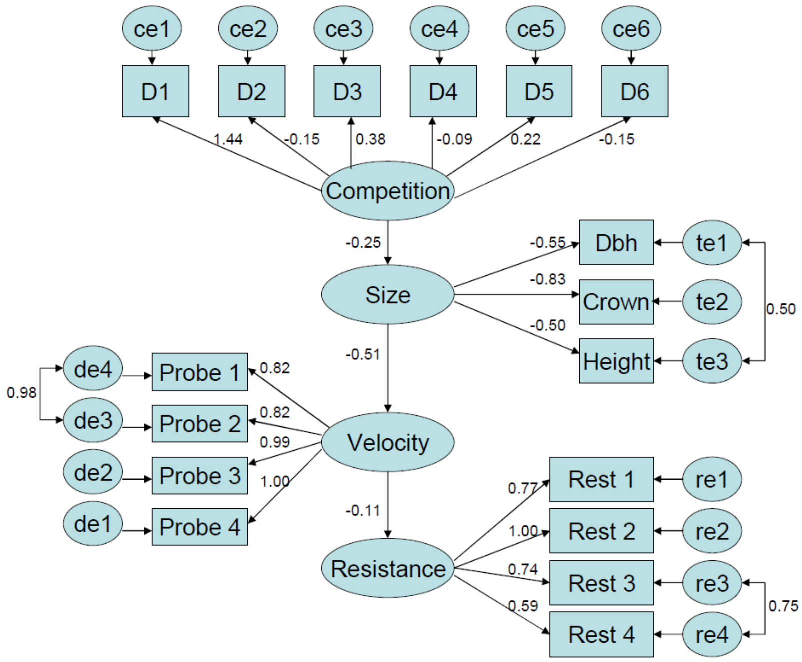

Figure 2. Structural equation model with standardized estimators. n=50, chisq=141.76, df=113, p=0.035

Competition

It is usually required to have at least four measured variables for each latent variable. For competition, it was possible to consider each area around the tree as a measured variable of competition. A total of six variables (areas) were used to estimate the competition variable. Also, tree dbh, tree height and distances between central tree and its neighbours are available. A competition index was used for integrating all these data to be entered directly into the model. The competition index is actually the product of two components of tree competition: height difference and crown radius ratio.

Height difference can be formulated as follow:

$$A = \frac{\pi}{2} - \arctan\left(\frac{h_a - h_v}{d}\right) \qquad [3]$$

where A is the angle of height difference in radians, h_a central tree height, h_v neighbor tree height and d the distance between the central tree and its neighbor. A low angle implies that the central tree "looks" at its neighbor and then it is dominant (Fig. 3). Conversely, a high angle, or more than 90 °, implies that the central tree is dominated by its neighbor. A nearby tree taller than the central tree will have a smaller angle if it lies at a great distance.

Crown radius ratio is represented by:

$$E = \frac{r_v}{r_a} \times \frac{(r_a + r_v)}{d} \qquad [4]$$

where *E* is the crown invasion, r_a the crown radius of the central tree and r_v the crown radius of the neighbor tree. *E* has a high score if the neighbor tree has a crown radius larger than the central tree and if the two crowns are touching.

Then, the competition index is:

$DI=A\times E$ [5]

This index has a minimum of zero corresponding to no competition. An index of one indicates that both trees have a similar dominance. An index greater than one indicates that the central tree is dominated.

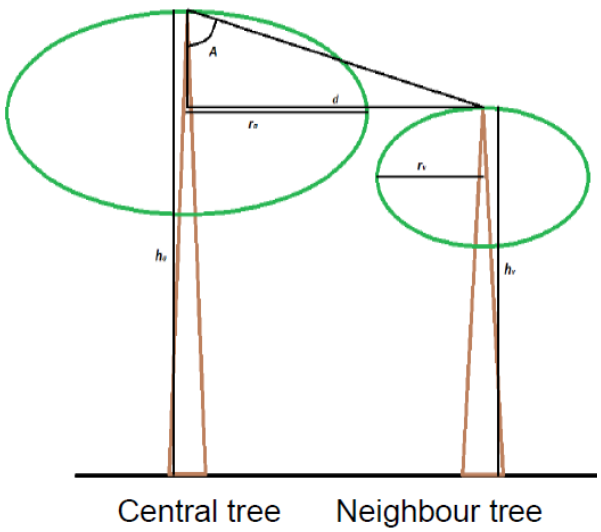

Figure 3. Trees attributes used for computing the competition index

Resistance

The resistance data are longitudinal as a vector of resistance values is produced for each sampled tree (Fig. 4). Therefore, they need to be transformed data to create the Resistance variable for the structural equation model. The transformation consists to create four variables from the mean values of resistance by quartiles.

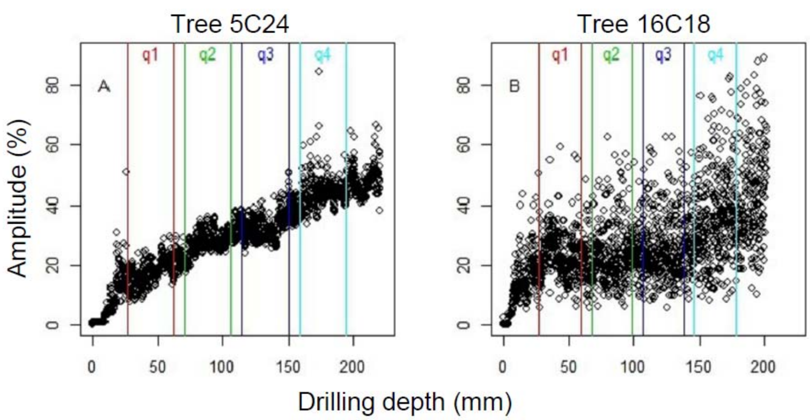

Figure 4. Examples of resistograph amplitude profile. The color bands represent the quartiles used in the structural equation model

Result and discussion

The component Competition of the structural equation model is significant with p = 0.365 (must be greater than 0.05). However, its parameters are still difficult to interpret. The component Resistance has the p value of 0.085. It is interesting to note that the interpretation of the estimators is very natural in this case. Indeed, there is an increase of resistance with the quantile. The quantile 4 is lower than the percentile 3, which is partly explained by the frequent presence of heart rot.

The complete structural equation model (Fig. 2) has the p value of 0.035, very close to 0.05. From the obtained results, Competition has a negative effect on Size, which subsequently negatively affects the stand density. Finally, a high stand density has the effect of causing a greater resistance to drilling. The negative relationship between Competition and Size seems appropriate. However, it is important to note that Size variable is difficult to interpret since the relationship between height and dbh does not have the same sign as that between crown area and height. Another problem of Size variable is that it represents the current state of the tree. However, competition does not affect tree size directly, but its growth (Dutilleul et al 1998). It is therefore necessary to complement the Size variable by a variable that measures growth e.g. radial increment in recent years of the life of the tree. Then, strong competition would tend to reduce growth and vice versa. The low sample size is another important gap that could explain the weak obtained results. According to Shipley (2002, p. 177), the sample size should be five times higher than the number of free parameters. Since the model contains 40 free parameters, a minimum sample size of 200 is needed to ensure the validity of the chi-square approximation.

Conclusion

Correlations were low between acoustic velocity, drill resistance, tree attributes and competition iondex. Although these correlations are still weak, they open the prospect of using the data of non destructive measurements such as acoustic probe and resistograph as complementary input with tree and stand attributes (dbh, crown, and competition index) for prescribing the intensity of thinning to a desired level of wood density. Such statistical models will greatly improve forest inventory by offering the possibility to assess the quality of individual trees. Thus, they will contribute to realize the full economic potential of the tree.

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