Wood Mechanical Properties and Discoloured Heartwood Proportion in Sugar Maple and Yellow Birch Grown in New Brunswick

Isabelle Duchesne,[a,]* Manon Vincent,[b] Xiaodong (Alice) Wang,[c,] Chhun-Huor Ung,[a] and D. Edwin Swift [d]

Rising interest in using wood in non-residential multi-story building structures opens up new opportunities for utilising low-grade hardwoods. The primary objective of this study was to evaluate the geographic variation in modulus of elasticity (MOE) and modulus of rupture (MOR) of sugar maple and yellow birch wood in relation to stand and tree characteristics for two regions in New Brunswick, Canada. Mixed effects statistical models were developed to test the effects of stand, tree, and wood sample variables. A second objective was to examine geographic variation in heartwood discolouration in relation to stand and tree characteristics. Between-tree differences (trees nested within sites) accounted for 44% and 35% of the total variation in yellow birch (MOE and MOR, respectively) and for 69% and 60% of total variation in sugar maple. The fixed effects explained only a very small part for the variation in MOE and MOR in the sugar maple data (10% for MOE and 5% for MOR). For sugar maple, mechanical properties (MOE and MOR) at 50% of the radius were considerably lower than those close to the bark, but this radial variation was not noteworthy for yellow birch. Discoloured heartwood proportion had no significant effect on wood mechanical properties.

Keywords: Low-grade hardwoods; End-use suitability; MOE; MOR; Sugar maple; Yellow birch; Statistical models; Geographic variation

*Contact information: a: Natural Resources Canada, Canadian Wood Fibre Centre, P.O. Box 10380, Québec, QC, G1V 4C7, Canada; b: Ministère des Forêts, de la Faune et des Parcs du Québec, 5700, 4e Avenue Ouest, Québec QC, G1H 6R1, Canada; c: Wood Technology and Engineering, Luleå University of Technology, Forskargatan 1, SE-931 87 Skellefteå, Sweden (Former postdoc at Canadian Wood Fibre Centre, Québec, Canada); d: Natural Resources Canada, Canadian Wood Fibre Centre, P.O. Box 4000, Fredericton, NB, E3B 5P7, Canada; *Corresponding author: isabelle.duchesne@canada.ca*

INTRODUCTION

Hardwood sawmills generate direct economic outcomes similar to the softwood industry, but at a smaller production scale (Trudelle *et al*. 2009). Over the past decade, the eastern Canadian hardwood lumber industry has been less competitive because of the limited availability of high-quality hardwoods combined with a particularly difficult economic situation (FPInnovations 2014). The decline in the overall quality of northern hardwood forests has been attributed to repeated selective harvest (high grading) practices of the past centuries.

In eastern Canada and northeastern United States, sugar maple (*Acer saccharum* Marsh.) and yellow birch (*Betula alleghaniensis* Britt.) are among the most important commercial hardwood species and have been typically used for the manufacturing of furniture, cabinetry, millwork, and flooring (Mullins and McKnight 1981). These appearance-based products generally require high-quality clear wood cuttings with a uniform colour that are free of visual defects on one or two board surfaces, depending on specific end-uses (Pearson 2009; McDonald 2010). In degraded stands, wood discolouration can reduce grade and volume yields and cause major value loss (Ohman 1968). However, although the availability of high-quality hardwoods has declined, the high density of these species makes them suitable for a range of structural applications. Indeed, in recent years, the interest in using hardwoods in structural applications has increased (Dill-Langer and Aicher 2014; Gong *et al.* 2015). Efforts have been made to add value to hardwood blocks by using them in engineered structural wood products (Verreault 2000). Hardwoods have been used for the production of structural plywood or glued-laminated materials, such as truck bedding (Sellers *et al*. 1988) and laminated wood railway ties (Gong *et al*. 2013). When stands contain small-diameter trees of marginal value for traditional uses, the lower-grade hardwood resources can be used in composite products, such as fibreboard, particleboard, and flakeboard, where product quality is not a direct function of stem quality (Sellers *et al.* 1988). The emergence of multi-story wood-frame buildings in Canada and European countries may also provide an opportunity to explore the potential use of lower-grade hardwoods in new structural applications such as in high-performance timber columns (Aicher *et al.* 2014; Candelario 2015). To this end, it is important to increase our knowledge of hardwood properties to ensure uniform or predictable quality of products from our forests. Compared with softwoods, hardwoods have received little attention in terms of characterising its wood fibre attributes such as stiffness and strength. Among the few studies available, Jessome (2000) and Kretschmann (2010) characterised the strength properties of sugar maple and yellow birch from eastern Canada and northeastern United States, respectively. However, mechanical property studies on hardwoods provide often limited or no information about stand growth conditions. Consequently, there is still a gap in our understanding of the relationships between wood fibre characteristics and stand growth conditions (Duchesne and Letarte 2013).

The objective of this study was to evaluate the geographic variation in modulus of elasticity (MOE) and modulus of rupture (MOR), and discoloured heartwood proportion (HW) of sugar maple and yellow birch wood in relation to stand and tree characteristics for two ecoregions of the province of New Brunswick, Canada. Mixed effects statistical models are developed in this study to test the effects of stand, tree, and wood sample variables on hardwood MOE and MOR.

EXPERIMENTAL

Stand and Tree Measurements

In the autumn of 2009, eight sites were selected in two ecoregions in New Brunswick (NB): the Central Uplands near Fredericton, and the Northern Uplands northeast of Edmundston (Table 1, Zelazny *et al.* 1989). Located in the northern hardwoods of the Acadian Forest Region (Rowe 1972), the study sites consisted primarily of various proportions of sugar maple (*Acer saccharum* Marsh.), yellow birch, red maple (*Acer rubrum* L.), and American beech (*Fagus grandifolia* Ehrh.), which are very typical of the hardwood resource in New Brunswick. All stands were unevenly aged and mature and had

had some partial harvesting (most recent cuts occurred 3 to 15 years before tree harvest). Because eastern North America has a long history of silvicultural activities, selective harvesting has been practiced over the last 100 years (Swift *et al*. 2013). At each site, two 11.28-m radius circular plots (400 m^2) were laid, in which the dominant tree height and the diameter at breast height (DBH) of each live merchantable tree larger than 9 cm were measured. Basal area (G) was averaged from the data of the two plots (Table 1). Thereafter, five sample trees were randomly selected per temporary plot, for a total of 10 trees per site. The 80 trees were harvested for analysis of lumber product volume and grade recoveries (Duchesne *et al.* 2012). However, for the modelling of mechanical properties, 18 trees could not be used because of internal defects (*e.g.*, checks, decay, and knots) and/or incomplete stand- or tree-level data, for a total number of 62 trees (Table 2). Sample tree DBH ranged between 24 and 46 cm for both species (Table 3). The measured tree attributes were stem diameter at 1.30 m (DBH_cm), total height (H_tot_m) and crown variables, *i.e.*, crown width (WidCr_dm), live crown length (lenCr_m), and crown area (Crown_area_m2). Tree age (Tree age) was also estimated based on the ring count on a disk cut at a stump height of approximately 15 cm above ground (no age correction).

Table 1. Study Site Descriptive Data

NB Ecoregion	Site No.	Name	Latitude	Longitude	Average Basal area G (m^2/ha)
Central Uplands	P1	Dunbar 2	46.14863371	-66.70091847	27
	P2	McLean's Brook	46.35785507	-66.87769976	32
	P3	6564	46.34212609	-66.25654978	25
	P4	8287	46.27486710	-66.94395485	20
Northern Uplands	P5	Edmundston (10206)	47.47825686	-68.12103826	20
	P6	St-Quentin West (10203)	47.59620063	-67.48962010	33
	P7	Campbellton (1366)	47.77314931	-66.66284493	24
	P8	St-Quentin East (10207)	47.50821680	-67.11357348	30

Table 2. Number of Trees and Small Clear Specimens by Site and Species; Specimen Location: A) Near the bark; C) 50% of radius

Site No.	**Sugar maple** ([1]missing data)			**Yellow birch**			
	No. of trees	No. of clear specimens		No. of trees	No. of clear specimens		Total specimens
		A	C		A	C	A + C
P1				7	7	7	14
P2	4	4	4	2	2	2	12
P3	7	7	6[1]				13
P4	5	5	5	5	5	5	20
P5	3	3	3	5	5	5	16
P6	9	9	9				18
P7	6	5[1]	6	1	1	1	13
P8	3	3	3	5	5	5	16
Total	37	36	36	25	25	25	122

Table 3. Stand and Tree Characteristics

Level	Variable	Sugar maple		Yellow birch	
		Mean ± Stdev[1]	Range	Mean ± Stdev	Range
Tree characteristics	DBH (cm)	33 ± 7.0	24.0 - 46.0	33.5 ± 6.5	24.0 - 46.0
	H (m)	16.9 ± 2.2	16.6 - 24.8	19.0 ± 1.2	16.7 - 21.9
	Age (years)	102.6 ± 40.4	57.0 - 221.0	112.0 ± 34.6	50.0 - 180.0
	Crown width (dm)	28.1 ± 6.8	11.0 - 39.7	31.8 ± 5.3	17.7 - 42.2
	Crown length (m)	11.9 ± 2.3	6.9 - 17.3	13.0 ± 2.1	7.3 - 16.5
	Crown area (m^2)	338.2 ± 119.7	75.5 - 647.6	370.4 ± 118.3	155.1 - 638.1
Stand characteristics	Basal area (m^2/ha)	27.7 ± 4.5	21.0 - 33.0	26.0 ± 3.8	21.0 - 33.0
	Mean dominant height (m)	20.9 ± 2.0	17.7 - 24.5	18.8 ± 1.1	17.4 - 21.4

[1]Stdev: Standard deviation

Small Clear Specimen Preparation and Testing in Static Bending

A 30-cm bolt was cut after the first sawlog of each sample tree. Because trees were bucked to maximise lumber recovery, the height at which bolts were cut varied between 1.8 m and 7.0 m (3.7 m on average), depending on tree quality. Expressed as the relative tree height, the bolts were extracted on average at 18% of the total tree height (range: 9% to 36%).

Heartwood diameter (HW_Diam_mm and HW_rel_Diam), defined as brown-reddish discoloured wood that is not white sapwood, was measured on the cross section of each bolt (average of north-south and east-west diameters). For each bolt, a slice including the pith was first sawn, from which two 10 mm x 10 mm x 190 mm small clear specimens were extracted: one near the bark in the sapwood (A), the other at 50% of the radius (C). These slices were sawn in the east-west direction, unless a major defect occurred. The 62 sample trees produced a total of 122 defect-free small clear specimens that could be successfully tested (Table 2).

For each specimen tested, the following data were recorded: location (Spec_Loc, A or C), number of rings per specimen (Nb_Ring), mean ring width (MeanRingW_mm), and sample height within the tree (Sample_H). Thereafter, specimens were placed in a conditioning room (20 °C, 65% relative humidity) until they reached an equilibrium moisture content of 12%.

MOE and MOR tests were performed at FPInnovations with an MTS ReNew Upgrade universal testing machine (MTS Headquarters, Eden Prairie, Minnesota, U.S.A.) following the ASTM-D-143-94 (ASTM 2007) standard test method for small clear specimens. Specimens were placed with growth rings horizontal and tested at 12% moisture content using a span of 140 mm. Basic density (oven-dry wood weight/green volume) of each specimen was measured according to ASTM-D-2395-07 (ASTM 2009). Table 4 is a summary of specimen characteristics.

Table 4. Small Clear Wood Specimen Characteristics and Average Mechanical Properties

	Sugar maple		Yellow birch	
Explanatory variables	Mean ± Stdev	Range	Mean ± Stdev	Range
HW diam (mm)[1]	62.3 ± 31.1	12.7 - 171.7	85.6 ± 38.1	23.7 - 185.0
HW relDiam (%)[1]	20.8 ± 8.1	6.0 - 45.2	27.6 ± 8.4	10.3 - 41.9
Nb ring[2]	6.4 ± 2.2	3.0 - 11.0	6.2 ± 2.0	2.0 - 11.0
Mean ring width (mm)[2]	1.8 ± 0.6	0.9 - 3.3	1.8 ± 0.7	0.9 - 5.0
Sample H (m)[2]	3.6 ± 1.3	1.8 - 7.0	3.7 ± 1.3	1.9 - 6.7
Basic density (kg/m^3)[2]	597.0 ± 27.8	522.6 - 654.5	551.6 ± 31.8	497.0 - 627.4
Response variables	Mean ± Stdev	Range	Mean ± Stdev	Range
MOE (MPa)	10684 ± 2172	5434 - 15008	10954 ± 2356	4064 - 14985
MOR (MPa)	113.2 ± 15.8	65.4 - 144.6	106.5 ± 18.7	44.2 - 136.7

[1] Measured on the transversal section of each 30-cm bolt (before cutting the two specimens)
[2] Measured on each specimen

Model Development for MOE and MOR

The dataset had a hierarchical structure, implying interdependence of observations. Specifically, MOE and MOR measurements were nested within trees, which were nested within sites. Mixed linear models were thus used to investigate variations within as well as among trees and sites (Brown and Prescott 2006). Random site and tree effects were included in the models to allow parameter estimates to vary around the population mean at the level of each grouping factor. Normality of variables was verified graphically and data transformation (centering) applied when needed.

Using the variables listed in Table 5, mixed models were developed in successive steps. First, three groups of models were built to described MOE and MOR variations with 1) tree, 2) stand, and 3) sample and wood attribute characteristics, then global models were built, which accounts for the joint effects of the tree and stand, tree and sample, tree, sample and stand characteristics on MOE and MOR variations. Interaction terms between Spec_Loc X Sample_H_m, Nb_ring_Spec X Sample_H_m, HW_Diam_mm X Spec_Loc, and H_tot_m X Sample_H_m were assumed to incorporate the effect of juvenile wood on mechanical properties. All *a priori* multilevel linear models were then compared to identify the main factors related to MOE and MOR variations in both yellow birch and sugar maple. Model selection was performed using the AICcmodavg package in R (Mazerolle 2012). This led to uncertainties regarding the selection of the best model to be assessed using a model averaging technique (also referred to as “multimodel inference”). The package computes the weighted estimates of the predictions for a given predictor variable across all models. The weighting of parameter estimates is given by the model probabilities, which are derived from Akaike's weights (Mazerolle 2006). Normality of residuals was verified graphically, and the multicollinearity between data and the distribution of residuals *vs*. predicted values was verified using a variance inflation factor (VIF).

Table 5. List of Explanatory Variables Tested for Modelling MOE and MOR

Grouping level	Variables	Description
Site properties	Gha_final_m2ha	Basal area of the sample plot measured in fall 2009
	H_plot_m	Mean dominant height
Tree properties	Tree_age	Age at stump height at approximately 15 cm above ground
	DBH_cm	Diameter at breast height 1.3 m
	H_tot_m	Total height of standing tree
	WidCr_dm	Live crown width
	lenCr_m	Crown length
	crown_area_m2	Crown area
	HW_Diam_mm	Discoloured wood diameter (heartwood of traumatic origin)
	HW_rel_Diam (%)	Discoloured wood diameter (heartwood) and total disc diameter ratio
Small clear specimen properties	Spec_Loc	Small clear specimen location in the cross section of the bolt
		A: specimen cut in the sapwood formed closest to the bark
		C: specimen cut at a relative position corresponding to 50% of the bolt radius
	MeanRingW_mm	Average ring width in the cross section of the small clear specimen tested
	Nb_ring_Spec	Number of full rings in the cross section of the small clear specimen tested
	Basic_Dens_kgm3	Wood basic density (oven-dry wood weight/green volume)
	Sample_H_m	Bolt height within tree
	MOE_MPa	Modulus of elasticity in static bending
	MOR_MPa	Modulus of rupture in static bending

RESULTS AND DISCUSSION

Hardwood Mechanical Property Models

Several candidate models were developed and compared for each species. For yellow birch MOR, five models appeared equivalent among all the models tested (Akaike weight of first models lower than 0.90, and delta AICc (Δ_i) < 2, Mazerolle 2006, data not shown). Three models included sample and tree variables, and two more complex models included interactions between Sample_H_m and other variables. The best model for predicting birch MOE included only sample and tree variables. For maple MOE and MOR, a dozen models appeared equivalent. All these models included only sample and tree variables for MOE, sample variables alone, and sample and tree variables for MOR. Using models averaging and the 95% confidence intervals (CI), it appears that only Nb_ring_Spec (CI= 261.84, 707.5), Tree_age (CI= -39.24, -4.07), and LenCr_m (CI= -756.38, -138.74) showed strong evidence of having a significant influence (effect $\neq$0) in yellow birch MOE variations. In birch MOR models, Nb_ring_Spec (CI= 1.06, 5.19) and Tree_age (CI= -0.39, -0.08) had a significant effect on MOR variations. Spec_Loc (CI= -1900.1, -745.61) was the only sample variable having a significant influence on sugar maple MOE while Spec_Loc (CI=-10.83, -1.77) and Nb_ring_Spec (CI= 0.27, 2.82) had a significant effect on sugar maple MOR variations. The fixed effects parameters estimates, standard deviation (Stdev) and summary statistics of final models are presented (Table 6). Thus, the final equations for models are:

Sugar maple $MOE_{ijk} = \alpha_0 + a_i + b_{j(i)} + \alpha_4 Spec\_Loc + e_{ijk}$ (1)

Sugar maple $MOR_{ijk} = \alpha_0 + a_i + b_{j(i)} + \alpha_2 Nb\_ring\_Spec + \alpha_4 Spec\_Loc + e_{ijk}$ (2)

Yellow birch $MOE_{ijk} = \alpha_0 + a_i + b_{j(i)} + \alpha_1 Nb\_ring\_Spec + \alpha_2 Tree\_age + \alpha_3 LenCr\_m + e_{ijk}$ (3)

Yellow birch $MOR_{ijk} = \alpha_0 + a_i + b_{j(i)} + \alpha_1 Nb\_ring\_Spec + \alpha_2 Tree\_age + e_{ijk}$ (4)

where α_0, α_1, α_2 and α_3 are the fixed effects parameters. The random elements a, b, and e are assumed to be independent and normally distributed. a_i denotes the site random effect $b_{j(i)}$ the tree nested in site random effect and e_{ijk} the within group error.

Table 6. Parameters Estimates, Standard Errors (SE), Variance Component (Stdev), and Summary Statistics of Final Models

		Sugar maple		Yellow birch	
		MOE	MOR	MOE	MOR
Parameter	Intercept (α_0)	11479.3 (403.3)	115.9 (3.4)	18997.7 (2048.3)	133.9 (8.8)
	Spec_Loc (C)	-1429.4 (272.9)	-4.8 (3.4)	-	-
	Nb_ring_Spec	-	0.6 (0.9)	487.0 (113.3)	3.2 (1.0)
	Tree_age	-	-	-21.7 (8.9)	-0.2 (0.1)
	LenCr_m	-	-	-433.5 (145.5)	-
Std. Dev.	Site	588.6	4.9	0.2	0.0
	Tree	1623.3	11.1	1173.7	9.21
	Residuals	1146.8	9.9	1326.6	12.5
Summary statistics	RMSE (MPa)	865.8	7.7	1073.7	10.5
	R^2	0.9	0.8	0.8	0.7
	R^2 (fixed only)	0.1	0.05	0.5	0.3

Results showed that between-site differences represented a negligible portion of the total variation for yellow birch mechanical properties in this study, while it accounted for about 20% of the total variation for sugar maple. However, between-tree differences (tree nested within sites) accounted for 44% and 35% of the total variation in yellow birch (MOE and MOR respectively) and for 69% and 60% of total variation in sugar maple. The fixed effects explained only a very small part for the variation in MOE and MOR in the sugar maple data (10% for MOE and 5% for MOR). The HW_Diam_mm effect and its interaction with Spec_Loc were tested, and these were not significant either in sugar maple or in yellow birch. Yellow birch age and crown length significantly affected MOE and MOR, but this was not the case for maple. Yellow birch MOE and MOR appeared significantly lower in older trees and birch MOE was lower in trees with long live crowns (Fig. 1). Older birch trees may lack vigour (senescence) and grow wood with lower mechanical properties. Jelonek *et al.* (2015) studied the effect of tree senescence on the properties of wood tissues in Scots pine (*Pinus sylvestris* L.). They found a marked decline in basic density and MOE after the tree age exceeded approximately 75 to 80 years, indicating a dynamic ageing process expressed in the gradual deterioration of wood tissue properties. In the North Shore region of Québec, Torquato *et al.* (2014) found that MOE and MOR in black spruce were higher in samples from stands of regular structure (mean tree age: 101 years) compared with that of very old stands of irregular structure (mean tree age: 165 years). It can be hypothesized that wood formation in maple and birch may follow a senescence pattern similar to that of softwoods with tree age. No information on the effects of tree senescence on hardwood properties was found, perhaps because the primary use of hardwoods is for appearance-based products.

On the other hand, long crowns of dominant trees may also confer lower mechanical properties when growth rates are excessive in relation to the normal growth of the species. Thus, it seems that we observe two interacting, complex mechanisms regulating birch wood formation and properties: one related to tree age and the other to growth rate.

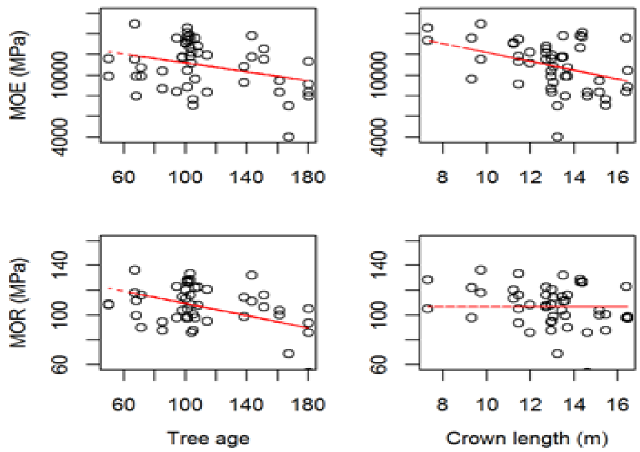

Fig. 1. Predicted MOE and MOR variations with tree age and crown length in yellow birch. Lines are the predicted values using fixed effects parameters only. Average crown length (13 m) was chosen within the equation to show fitted MOE and MOR variations with age, whereas average tree age (112 years old) was chosen within the equation to show fitted MOE and MOR variations with crown length.

Geographic Variation in Mechanical Properties

Small clear specimen average MOE and MOR values are shown in Table 4. Compared with data in the literature (Jessome 2000), the sugar maple average value was 24% lower for MOE (14100 MPa *vs*. 10684 MPa in this study) but similar for MOR (115.0 *vs*. 113.2 MPa). For yellow birch, MOE was 22% lower (14100 MPa *vs*. 10954 MPa in this study) and similar for MOR (106.0 *vs*. 106.5 MPa in this study). A simple Pearson correlation analysis indicated a strong positive link between MOE and MOR for both species (r = 0.87 for sugar maple and 0.85 for yellow birch).

MOE and MOR variation between sites appeared larger for sugar maple, while birch MOE and MOR appear relatively homogeneous between sites (Fig. 2). These results should be regarded with caution because of the very limited number of sample trees analysed at each site, especially for birch (Table 2). As shown in the previous modelling section, site variables had no effect on MOE and MOR. There was no statistically significant difference in MOE and MOR between the ecoregions of Northern and Central Uplands for both species, suggesting that growth conditions within the Acadian Forest region were comparable, or did not vary to the point of inducing notable changes in MOE and MOR. The relationship between mechanical properties and specimen basic density was similar for the two species: MOE stayed more or less constant throughout the range of wood densities measured while MOR tended to slightly increase with increasing density (but the trend was not statistically significant).

The effect of specimen location on MOE and MOR is shown in Fig. 3. For maple, MOE from clearwood located at 50% of the radius (C) was 9961 MPa, and it increased to 11407 MPa near the bark (A) (+14.5%), while for MOR it increased from 110.0 MPa at position C to 116.4 MPa at position A, (+5.8%). For yellow birch, MOE increased from 10471.8 MPa (C) to 11436.0 MPa (A) (+9.2%), and MOR from 104.9 MPa (C) to 108.1 MPa (A) (+3.1%), but this variation, which is related to specimen location, was not statistically significant. For maple, specimens near the bark (A) were stiffer than those at position C at all sites. For birch, four out of six sites had stiffer wood near the bark (A). The two sites that showed the contrary also had the smallest number of samples of all birch sites: P2 (2 trees) and P7 (1 tree). This suggests that birch may follow a similar radial trend as maple, but a more extensive sampling would be needed to verify this.

Geographic Variation in Discoloured Heartwood

In this study, heartwood refers to a darker brown-reddish discolouration of traumatic origin (also called red heartwood) developed in sugar maple and yellow birch wood as a result of tree injuries and invasion by microorganisms (Shigo 1967; Hallaksela and Niemistö 1998; Drouin *et al*. 2009). These hardwoods do not develop a regular, genetically-programmed "true"-coloured heartwood as in other species (e.g., oaks). Traumatic heartwood discolouration has no effect on wood mechanical properties (Shmulsky and Jones 2011). Similarly, no effect on the mechanical properties of wood as a result of a change from sapwood to regular, "true"-colored heartwood has been found in most species in the United States (USDA 1966), and for white and red oaks in Europe (Merela and Cufar 2013).

Discoloured heartwood proportion varied greatly from site to site and was larger in birch compared with maple (27.6% *vs*. 20.8%, Fig. 4). It tended to increase with tree age only for birch (Fig. 5). In the province of Québec, red heartwood proportions of 36.4% and 36.8% were reported for sugar maple and yellow birch, respectively (Havreljuk *et al.* 2013). The proportion of discoloured wood had no significant effect on small clear mechanical properties, which concurs with the literature (Shmulsky and Jones 2011).

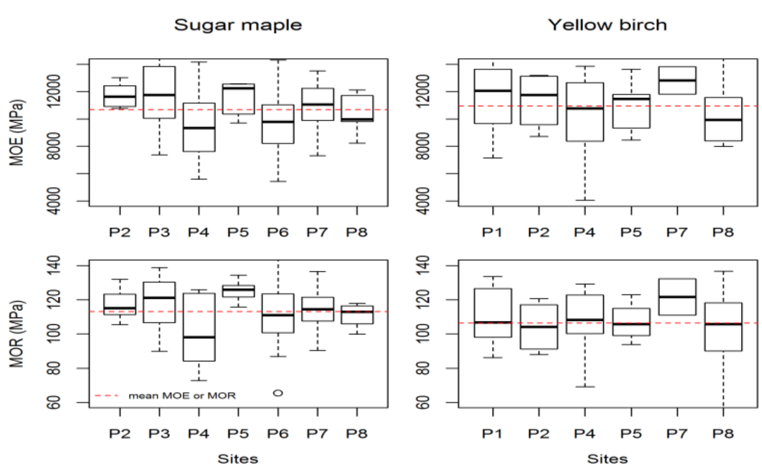

Fig. 2. Box-plot of MOE and MOR variations in relation to geographic sites. The New Brunswick Ecoregions of Central Uplands and Northern Uplands are represented by study sites P1 to P4 and P5 to P8, respectively.

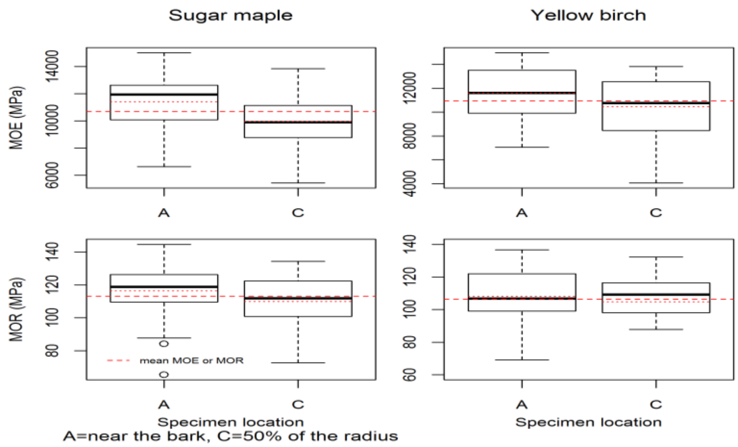

Fig. 3. Box-plot of MOE and MOR variations with specimen location (A: near the bark, C: 50% of the radius). Bold black lines show median of the sample. Thin, dotted lines show the average MOE and MOR for each location.

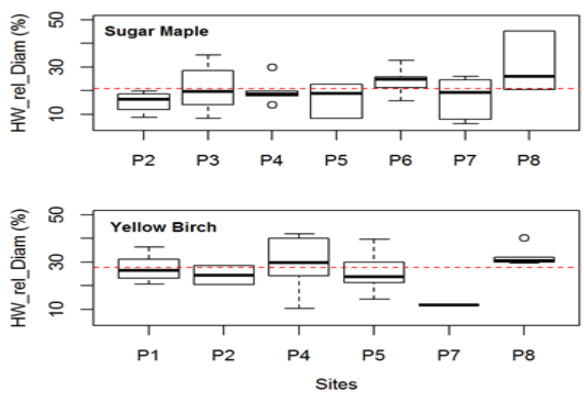

Fig. 4. Heartwood proportion (%) in relation to sites for sugar maple and yellow birch in New Brunswick's ecoregions of Central (P1 to P4) and Northern (P5 to P8) Uplands

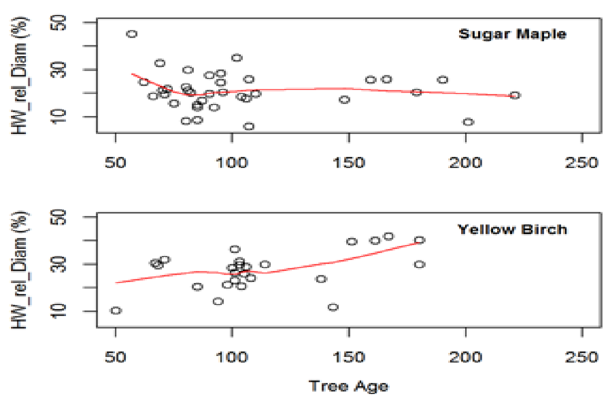

Fig. 5. Heartwood proportion (%) of sugar maple and yellow birch in relation to tree age

CONCLUSIONS

1. In this study, there was no significant effect of ecoregion on hardwood MOE and MOR. In the models developed, a large amount of MOE and MOR variation was explained by random effects, which means that the explanatory variables tested poorly explained the response variables, especially for sugar maple where fixed effects explained only 10% and 5% of MOE and MOR variation, respectively. These results were due to between-site variation that was more important in sugar maple models compared with yellow birch models.

2. Clear wood specimens located at 50% of the radius showed a MOE and MOR significantly lower than those located close to the bark for maple, but not for birch. MOR in maple was also slightly affected by the number of rings by specimen (growth rate indicator). In birch, the number of rings per specimen as well as tree age significantly affected MOE and MOR, both of which decreased with tree age. Crown length negatively affected birch MOE.

3. A positive relationship was observed between tree age and heartwood proportion, only for birch. Heartwood proportion did not have any significant effect on MOE and MOR.

4. The indication that crown length and age affected internal wood attributes in yellow birch opens up the possibility for forest managers to positively manipulate tree growth conditions to obtain specific internal wood characteristics.

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