

1 **Modeling black spruce wood fiber attributes**
2 **with terrestrial laser scanning**

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25 **Abstract**

26 A model comparison approach, based on the Akaike's information criterion, was used to
27 evaluate the contribution of terrestrial laser scanning (TLS) to the estimation of wood
28 fiber attributes at the tree level for black spruce (*Picea mariana* (Mill.) B.S.P.) trees
29 growing in Newfoundland, Canada. Substantial efforts were made to acquire, process,
30 and develop accurate and detailed metrics of the tree, its crown, and its immediate
31 environment. Based on the resulting data set, significant relationships were found, and
32 models were successfully developed, using only TLS metrics, for predicting wood fiber
33 attributes. The models accounted for 47%, 33%, 51%, 44%, and 52% of variance in wood
34 density, coarseness, fiber length, microfibril angle, and modulus of elasticity respectively,
35 with root mean square error values of 46 kg/m³, 37 µg/m, 0.20 mm, 3.5 °, 2.3 GPa. Our
36 ability to estimate the wood fiber attributes was improved by combining TLS metrics
37 with conventional field measurements. This study demonstrates that the use of TLS
38 metrics improves the estimation of the wood fiber attributes at the tree level beyond that
39 possible with conventional field measurements.

40 **Keywords:** forest inventory, terrestrial laser scanning, modeling of wood fiber attributes,
41 non-destructive measurement of trees, black spruce boreal forest.

42 **Introduction**

43 Newfoundland and Labrador's forest products industry directly and indirectly employs
44 over 5,500 workers in pulp and paper, sawmilling, harvesting, and value-added sectors
45 (Government of Newfoundland and Labrador 2015; 2018a). The pulp and paper sector
46 accounts for approximately 50% of total revenues and uses 1.2 million cubic meters of
47 local timber, predominantly balsam fir (*Abies balsamea* (L.) Mill.) and black spruce
48 (*Picea mariana* (Mill.) B.S.P.). The fiber attributes of both species greatly influence the
49 processing, quality, and uniformity of the end products. For example, refining black
50 spruce pulp requires more energy because of its higher density and longer fibers (Li et al.
51 2011). Black spruce also produces thermomechanical pulping with significantly higher
52 strength properties, whereas balsam fir provides superior optical properties because of its
53 lower cell wall thickness. However, the supply is never consistent in quality because the
54 fiber attributes vary locally and spatially for a given species, as shown for black spruce in
55 eastern Canada (Lessard et al. 2014; Giroud et al. 2017). Defo et al. (2015) recently noted
56 the importance of knowing the quantity and quality of the forest resource for matching
57 the right fiber to the right end use to maximize product value and also to understand the
58 effects of our forest management decisions on wood quality.

59 Wood fiber quality is determined by intrinsic wood properties. One growth ring is
60 produced each year, consisting of a zone of earlywood followed by a zone of latewood
61 (Larson 1969). Latewood is characterized by denser cells with a lower microfibril angle
62 (MFA) (Donaldson 2008). The local growth conditions either directly or indirectly
63 influence the crown development, and consequently, the width of the growth rings and

64 the relative proportion of earlywood to latewood within the rings. The link between tree
65 characteristics and wood fiber attributes is often limited, but significant, at the tree level.
66 In 1984, Alemdag reported weak relationships between wood density and diameter at
67 breast height (DBH), total height, and age for black spruce and 27 other species in
68 Ontario, Canada. More recently, Giroud et al. (2017) observed weak correlations between
69 wood density, modulus of elasticity (MOE), and stem characteristics for the main boreal
70 species of Quebec, including black spruce. Similar correlations were found between
71 wood density and crown characteristics for black spruce and balsam fir in Newfoundland
72 (Groot and Luther 2015). Groot et al. (2015) suggested that the weakness of the
73 relationship between crown characteristics and wood density could be a consequence of
74 the relatively simple description of the tree crown (width, length, and ratio) in
75 conventional inventories. Groot et al. (2015) also suggested this limitation could be
76 addressed with remote sensing technologies that measure the crowns more accurately.
77 Airborne and terrestrial laser scanning (ALS and TLS) can provide a wide range of forest
78 metrics for modeling purposes. The proof-of-concept was recently demonstrated for
79 balsam fir and black spruce with the prediction of plot-level wood fiber attributes using
80 only ALS data as covariates (Luther et al. 2014; Pokharel et al. 2016). Wood fiber
81 attribute models were also successfully developed for balsam fir and black spruce in
82 Newfoundland using a suite of local structural metrics derived from TLS data (Blanchette
83 et al. 2015). Terrestrial laser scanning can also provide metrics such as crown
84 competition indices at the tree level (Martin-Ducup et al. 2016).

85 In this study, wood fiber attribute estimation was further investigated at the tree level for
86 black spruce trees growing in Newfoundland, Canada. More specifically, objectives were

87 to (i) establish a set of metrics to characterize the tree, its crown, and its immediate
88 environment using TLS data; (ii) develop a list of candidate models, with and without
89 TLS metrics, to estimate the basic density, coarseness, fiber length, MOE, and MFA; (iii)
90 and compare these models and determine the contribution of TLS for modeling wood
91 fiber attributes. The study focused on key fiber attributes that were identified, following a
92 broad consultation of experts across Canada, as key important attributes for industry
93 (Natural Resources Canada 2010). Although Blanchette et al. (2015) demonstrated the
94 potential of TLS for modeling wood fiber attributes at the plot level, to our knowledge,
95 this is the first study to model these attributes at the tree level using metrics derived from
96 TLS data.

Draft

97 **Materials and methods**

98 **Study area and data collection**

99 The island of Newfoundland is the easternmost region of Canada. The boreal forest cover
100 makes up about 46% of its total area (111,390 km²), the remainder consisting of lakes,
101 rivers, and wetlands (Government of Newfoundland and Labrador 2018b).

102 Newfoundland's forests are mainly dominated by balsam fir and black spruce, mixed
103 with some hardwoods. Black spruce accounts for approximately one-third of the forests
104 of the island. This slow-growing species grows in a variety of conditions, including very
105 wet and dry soils. Black spruce is the dominant species across much of central
106 Newfoundland, where forest fires are more common. Elsewhere, forests are dominated by
107 balsam fir in pure or mixed stands.

108 Data used were a subset of a larger data set collected and analyzed as part of the
109 Newfoundland Fibre Inventory Project (Lessard et al. 2014; Luther et al. 2014). In the
110 current study, 16 sites representing black spruce growing in mature stands of medium site
111 quality were retained. Table 1 shows site location and characteristics. A total of ten
112 merchantable-sized black spruce trees per site were initially core sampled to measure the
113 wood fiber attributes. Field data were collected on these trees, including diameter at
114 breast height (DBH), total tree height, and crown measurements as described by Groot
115 and Luther (2015; Table 2). Crown length was determined by subtracting base of live
116 crown from total tree height. Crown radius was computed as the average value of two
117 crown width measurements (North–South and East–West). Crown surface area was

118 determined from crown radius and crown length, assuming a conical crown. Crown
119 density was assessed on a scale of 1 to 3, with 1 representing >66% density and 3 <33%
120 density. Basal area of larger trees (BAL) was calculated by comparing DBH of cored
121 trees with the DBH distribution.

122 Terrestrial laser scanning data acquisition and processing is described in Blanchette et al.
123 (2015). The TLS scans were acquired using a Z+ F Imager® 5006i (Zoller + Fröhlich
124 GmbH, Wangen im Allgäu, Germany) operated at 0.036° angular resolution. Each site
125 was scanned using four peripheral and one central viewpoints in order to include as many
126 cored trees as possible, reducing signal occlusion (Fig. 1). Each scan was aligned with
127 circular black and white targets. Six targets were visible from the central viewpoint,
128 whereas a minimum of three visible targets was required for each peripheral scan
129 location. A filtering procedure was also applied to remove all noise points using Z+F
130 LaserControl® version 8.1.3 (Zoller + Fröhlich GmbH). The TLS scene including all the
131 cored trees was about 25 m × 25 m using this protocol. Because of the occlusion and
132 scanning limitations in forests, not all the cored trees were visible within a TLS scene.
133 The final data set consisted of 69 visible cored trees (hereafter referenced as “target”
134 trees) from 16 different sites.

135 **Tree-level metrics derived from TLS point clouds**

136 Conventional inventories do not measure competition and terrain features at the tree
137 level, and description of the crown, when made, is highly simplified (Groot et al. 2015).
138 Tree-level metrics were derived from TLS point clouds to describe as precisely as

139 possible the tree, its crown, and its immediate environment in terms of competition and
140 local topography (Table 2). Cylinders were thus isolated from the TLS scenes using a
141 semi-automatic procedure in the Computree platform version 3.0 (Othmani et al. 2011;
142 Fig. 2). The cylinder diameter (\emptyset) was estimated as a function of the highest point of the
143 canopy (*Canopy_MAX*) inside an upside-down cone placed at the tree base with a 30°
144 opening angle. This angle value was chosen by trial and error to obtain a representative
145 area for the computed metrics according to the canopy height. Highest point of the
146 canopy and coordinates (x, y, z) of each tree base were manually measured using
147 FARO® SCENE version 5.0.1 (Faro Technologies Inc., Lake Mary, Florida, USA).

$$148 \quad \emptyset_i = 2 \tan(15^\circ) \text{Canopy_MAX}_i \quad (1)$$

149 where \emptyset_i is the estimated diameter of cylinder *i*, and *Canopy_MAX_i* is the highest point of
150 the canopy of cylinder *i*.

151 A suite of metrics was computed to describe the canopy structure and the local
152 topography within the cylinders as detailed by Blanchette et al. (2015). A Digital
153 elevation model (DEM), digital surface model (DSM), and canopy height model (CHM)
154 were computed for each cylinder scene using a grid of 25 cm x 25 cm resolution with
155 TIFFS© version 8.0 beta (Globalidar, Honolulu, Hawaii, USA). This resolution was
156 chosen to reduce the amount of data while retaining as much detail as possible. Mean and
157 standard deviations of the canopy model (CHM_MEAN, CHM_STD) were extracted to
158 describe the canopy height and its level of variance. Canopy surface roughness was
159 estimated by a rumple index (CHM_RUMPLE) computed as the ratio of the 3D canopy

160 surface over its 2D projection (Kane et al. 2010). Vegetation density was estimated by a
161 volume-to-area ratio index (CHM_RATIO) computed as the volume present between the
162 reference plane given by the DEM and the DSM surface. Relative elevation difference
163 was calculated as the difference between the lowest and highest points of the DEM within
164 the cylinder (DEM_EL_DIF). Standard deviation of elevation (DEM_EL_STD) was also
165 determined. A rumple index was computed in the same manner as for the canopy to
166 characterize the ground surface roughness (DEM_EL_RUMPLE). The mean slope and its
167 standard deviation were also estimated within each cylinder from the DEM
168 (DEM_SL_MEAN, DEM_SL_STD).

169 A suite of metrics was then computed to characterize the stem competition within the
170 cylinders as detailed by Blanchette et al. (2015). One-meter thick slices centered at 1.5 m
171 above ground were extracted from each scene (Huang et al. 2009). Each slice was
172 manually filtered to keep only the points from circular sections related to the trunks of
173 standing trees. The location of each standing tree was manually recorded using
174 PointStream© version 3.0, as a point cloud viewer (Arius Technology Inc., Vancouver,
175 British Columbia, Canada). Stem density (TLS_STEMS) was computed within the
176 cylinders. Using the stem coordinates, the observed average distance between neighbors
177 (TLS_DISTANCE) was also calculated (Blanchette et al. 2015). An aggregation index
178 was then computed as the ratio of the observed versus expected distance between
179 neighbors (TLS_RATIO) (Clark and Evans 1954). This metric provides a direct measure
180 of “dispersion” or “clustering” of stems surrounding each target tree. The smaller the
181 ratio, the higher the competition for space among neighboring trees.

182 The target trees were then isolated from the cylinders using a semi-automatic procedure
183 in Computree platform version 3.0 (Othmani et al. 2011; Fig. 2). Tree height (TLS_TH),
184 base of live crown (TLS_CR_BLC), and crown length (TLS_CR_LGT) were manually
185 measured using FARO® SCENE version 5.0.1 (Faro Technologies Inc.). The points
186 belonging to the crown of each target tree were exported from Computree. The point
187 clouds were then voxelized using “VoxR” library (Lecigne et al. 2015) and R statistical
188 and programming language version 3.0.2 (R Development Core Team 2018). A voxel
189 size of 10 cm was chosen to represent the geometry of the crown in sufficient detail. A
190 3D alpha-shape reconstruction was applied to measure the surface (TLS_CR_SA) and
191 volume (TLS_CR_VOL) of each crown using the “alphashape3d” package in R (Lafarge
192 and Pateiro-Lopez 2017). Crown density (TLS_CR_DEN) was also estimated by dividing
193 the volume of non-empty voxels by the crown volume.

194 Three indices were computed to characterize the canopy competition within the cylinders
195 as detailed by Martin-Ducup et al. (2016): the canopy pressure index (CPI), the canopy
196 heterogeneity index (CHI), and the canopy density index (CDI). The immediate
197 vegetation surrounding each target tree was isolated from the cylinders using an upside-
198 down cone placed at the crown base with a 30° opening angle (Fig. 2). The point clouds
199 were voxelized using the same 10 cm voxel size as that used on the crowns of the target
200 trees (“VoxR” library, Lecigne et al. 2015). Canopy pressure index was computed as
201 follows:

$$202 \quad CPI = \frac{1}{n} \sum_{i=1}^n \frac{H_i V_i}{d_i} \quad (2)$$

203 where n is the number of cells in the raster, V_i is the number of non-empty cells in the Z
 204 direction above the raster cell i , d_i is the distance between the cell i and the projected
 205 center of the crown, and H_i is the mean height of the voxels of the cell i .

206 The spatial dispersion of the surrounding vegetation was estimated by the CHI computed
 207 as a Clark and Evans aggregation index based on the XY coordinates of each cell of the
 208 raster (Clark and Evans 1954). A CDI was also calculated as the ratio between the
 209 volume occupied by non-empty voxels and the total volume of the cone.

210 **Analysis of wood fiber attributes**

211 The 12 mm diameter increment cores were extracted at breast height from target trees.
 212 Cores were sent to the FPInnovations laboratory in Vancouver, British Columbia. After
 213 an acetone extraction, the samples were cut into radial strips of 2 by 7 mm (tangentially
 214 by longitudinally), and conditioned at 40% relative humidity and 20°C to reach a wood
 215 moisture content of 8%. Pith-to-bark profiles of wood density, stiffness (MOE), MFA,
 216 and coarseness were measured using SilviScan™ technology (Evans 1994, 2006). Wood
 217 density was determined at 25-µm radial resolution using the X-ray densitometer unit of
 218 SilviScan™. The wood density at 8% moisture content was then converted to basic
 219 density (BD), which is the most commonly used definition. Basic density is defined as
 220 the ratio between the oven-dry mass of a wood sample and its green volume and was
 221 calculated as follows (Siau 1995):

$$222 \quad \text{BD} = \frac{1000 \times D_8}{1080 + 0.22 \times D_8} \quad (3)$$

223 where BD is basic density and D_8 is density at 8% moisture content. It is assumed that the
224 fiber saturation point is 30% and that the water density is 1000 kg/m^3 .

225 Core measurements, such as the average ring width (RW) and the number of rings (RN),
226 were determined from the density profiles. Microfibril angle was determined by the X-ray
227 diffractometer unit of SilviScan™. Modulus of elasticity was estimated using the density
228 and the coefficient of variation of the X-ray diffraction profile intensity. Coarseness
229 (COA) was calculated by combining the profiles of wood density and tracheid diameter
230 obtained by image analysis with SilviScan™. Fiber length (FL) was also measured at the
231 FPInnovations lab by analyzing a fiber solution made from macerated wood cores with a
232 high-resolution fiber quality analyzer (HiRes FQA, OpTest Equipment Inc., Hawkesbury,
233 Ontario, Canada). The HiRes FQA system collects and analyzes images of fibers from the
234 pulp solution. Length-weighted fiber length was used as it corrects the natural bias
235 associated with fiber-wall fragments, also called fines (Robertson et al. 1999). Depending
236 on the total age of the samples, fiber length was acquired in two or three age classes,
237 corresponding to juvenile wood (age 1–30), transition wood (age 31–60), and mature
238 wood (age 61+). Samples were run in duplicate for each age class, and the results
239 averaged to get a single value by age class. Wood fiber attributes were averaged
240 assuming a circular shape of the rings. Wood fiber attributes are thus average estimates of
241 the stem cross-section at breast height.

242 **Statistical analysis**

243 Pearson's correlations were estimated to assess the strength of linear relationships
244 between the wood fiber attributes (BD, COA, FL, MOE, MFA) and the metrics of the

245 target tree and its immediate environment, measured during the forest inventory or
246 derived from TLS (PROC CORR, SAS 9.3, SAS Institute Inc., Cary, North Carolina,
247 USA). A model comparison approach was then used to ensure that all the potential
248 categories of covariates would be tested for their ability to predict wood fiber attributes.
249 Seven sets of candidate models were retained to evaluate the contribution of different
250 covariate groups: (1) the “CORE” set included the number of rings, the log
251 transformation of the ring number, and the average ring width; (2) the “STEM” set
252 included DBH, tree height, slenderness, and basal area of larger trees; (3) the
253 “STEM+CROWN” set contained all covariates of the “STEM” set plus the crown
254 measurements measured in the field; (4) the “STEM+CROWN+CORE” set contained all
255 covariates of the three sets; (5) the “TLS” set contained all metrics derived from the TLS
256 data; (6) the “STEM+CROWN+TLS” set contained all covariates of the three sets; and
257 (7) the “STEM+CROWN+CORE+TLS” set contained all of the available covariates
258 (Table 2). Within each set of models, all possible combinations were tested up to a
259 maximum of three covariates. Candidate models with strongly correlated covariates were
260 removed. Correlation coefficient >0.8 or <-0.8 was considered as evidence of collinearity
261 between two covariates.

262 Linear mixed-effects models were developed for estimating the wood fiber attributes at
263 the tree level (PROC MIXED, SAS 9.3, SAS Institute Inc.). A site random effect was
264 added to all models to account for within-site correlation as follows:

$$265 \quad Y_{ij} = a_0 + a_1 COV1_{ij} + a_2 COV2_{ij} + a_3 COV3_{ij} + u_i + \varepsilon_{ij} \quad (4)$$

266 Where Y_{ij} is one of the wood fiber attributes of target tree j in site i , a_0 to a_6 the fixed
267 effect parameters, $COV1$ to $COV3$ the three covariates, u_i the normally distributed site
268 random effect parameter ($u_i \sim N(0, \sigma_i^2)$), and ε_{ij} the residual error ($\varepsilon_{ij} \sim N(0, \sigma^2)$).

269 The models were fitted by maximum likelihood to find the best model for the fixed effects.
270 The model with the lowest Akaike's information criterion for small sample size (AICc)
271 was considered as the best model for a given set of covariates (Burnham and Anderson
272 2003). Delta AICc ($\Delta AICc$) and Akaike weights (ω_i) were also computed for model
273 comparison. The parameters of the most parsimonious models were subsequently re-
274 estimated using a restricted maximum likelihood (REML) approach. The goodness of fit
275 was assessed by computing the marginal pseudo-R² as described by Nakagawa and
276 Schielzeth (2013). The marginal pseudo-R² is only concerned with variance explained by
277 fixed effects. No model averaging or cross-validation procedures were applied because
278 the objective was only to evaluate the contribution of different sets of covariates for
279 modeling wood fiber attributes at the tree level.

280 **Results**

281 **Correlative relationships**

282 Table 3 shows Pearson's correlation coefficients between the wood fiber attributes and
283 the most influential covariates according to our modeling results. A magnitude of
284 between 0.5 and 0.8 usually indicates moderate correlation, whereas a magnitude of more
285 than 0.8 indicates strong correlation. Highly significant correlations were found between
286 the wood fiber attributes and the core measurements. Moderate linear relationships were
287 obtained with the ring number and the log transformation of the ring number (RNLN),
288 with correlation coefficients between 0.47 and 0.63, in absolute values. The fiber
289 attributes increase with age and then stabilize at maturity, except for MFA, which
290 decreases with age until maturity. Moderate linear relationships were also observed with
291 the average ring width, with correlation coefficients between 0.56 and 0.70, in absolute
292 values. The narrower the ring, the lower the MFA and the higher the other fiber
293 attributes.

294 Many highly significant correlations were found between the wood fiber attributes and
295 the tree measurements (Table 3). Weak to moderate linear relationships were obtained
296 with correlation coefficients between 0.26 and 0.58, in absolute values. Diameter at
297 breast height was negatively related to BD. Tree height (TH) was positively related to
298 fiber length and negatively to MFA. The higher the slenderness ratio (HD), the lower the
299 MFA and the higher the other fiber attributes, except for fiber length (non-significant).
300 Basal area of larger trees (BAL) was positively related to wood density. Base of live

301 crown (CR_BLC) was significantly correlated with all wood fiber attributes. The higher
302 the base of live crown, the lower the MFA and the higher the other fiber attributes.

303 Crown length (CR_LGT) was negatively related to wood density.

304 Many highly significant correlations were also found between wood fiber attributes and
305 TLS metrics (Table 3). Weak to moderate linear relationships were obtained, with
306 correlation coefficients between 0.24 and 0.65, in absolute values. The wood fiber
307 attributes were more weakly correlated with the base of live crown derived from TLS
308 (TLS_CR_BLC) than with the base of live crown measured in the field (CR_BLC).

309 Crown density (TLS_CR_DEN) was negatively correlated to fiber length. Crown volume
310 (TLS_CR_VOL) was negatively related to wood density. The canopy competition indices
311 derived from TLS (CPI, CHI, CDI) were all positively correlated with wood density.

312 Significant correlations were also found with the heterogeneity and variability of the
313 canopy height model (CHM_RUMPLE, CHM_STD). The more irregular the vertical
314 forest structure, the lower the MFA, and the higher the other wood fiber attributes. Wood
315 fiber attributes were significantly correlated with local topography (DEM_EL_RUMPLE,
316 DEM_SL_MEAN). The more irregular the topography surrounding the target tree, the
317 higher the MFA, and the lower the other fiber attributes. Highly significant correlations
318 were also found with stem competition indices derived from TLS (TLS_RATIO,
319 TLS_DISTANCE). The lower the competition for space among neighboring trees, the
320 higher the MFA, and the lower the other fiber attributes. Similarly, the longer mean
321 distance between trees, the higher the MFA, and the lower the other fiber attributes.

322

323 **Fiber attribute models**

324 The candidate models for estimating wood fiber attributes were ranked according to their
325 AICc scores (Table 4). The “STEM” models provided essentially no support for the top-
326 ranking models with deltas (Δ_i ; AICc differences) greater than 10. Adding crown
327 measurements into the “STEM” models slightly reduced the AICc scores, but the
328 contribution of the “STEM+CROWN” models was limited with deltas greater than 10,
329 except for estimating coarseness ($\Delta_i=6$; $w_{\text{BEST}}/w_i=25$ times less support than the top-
330 ranking model). The base of live crown accounted for 33%, 54%, 65%, and 51% of the
331 explained variation in basic wood density, coarseness, MFA, and MOE, respectively. The
332 “CORE” models were always more parsimonious than the “STEM+CROWN” models for
333 estimating wood fiber attributes. The “CORE” models provided substantial support for
334 estimating coarseness ($\Delta_i=2$; $w_{\text{BEST}}/w_i=3$), less support for estimating fiber length ($\Delta_i=8$;
335 $w_{\text{BEST}}/w_i=52$), MFA ($\Delta_i=6$; $w_{\text{BEST}}/w_i=19$), and MOE ($\Delta_i=3$; $w_{\text{BEST}}/w_i=4$), and essentially
336 no support for estimating wood density ($\Delta_i=16$; $w_{\text{BEST}}/w_i=3\ 294$). The
337 “STEM+CROWN+CORE” model was the top-ranking model for estimating wood
338 density, but its contribution was limited for estimating other wood fiber attributes. The
339 “CORE” and “STEM+CROWN+CORE” models were the same for coarseness, MFA,
340 and MOE, with only core measurements retained in the best models.

341 Predictive models were successfully developed to estimate wood fiber attributes using
342 only TLS metrics (Table 4). The “TLS” models provided substantial support for
343 estimating MFA ($\Delta_i=1$; $w_{\text{BEST}}/w_i=2$) and MOE ($\Delta_i=2$; $w_{\text{BEST}}/w_i=2$), less support for
344 estimating coarseness ($\Delta_i=7$; $w_{\text{BEST}}/w_i=30$) and fiber length ($\Delta_i=4$; $w_{\text{BEST}}/w_i=8$), and

345 essentially no support for estimating wood density ($\Delta_i=21$; $w_{\text{BEST}}/w_i=36\ 316$). The crown
346 volume (TLS_CR_VOL) accounted for 48% of the explained variation in basic wood
347 density. The structural characteristics of the canopy height model (CHM_RUMPLE,
348 CHM_STD) accounted for 56%, 67%, 25%, and 30% of the explained variation in
349 coarseness, fiber length, MFA, and MOE, respectively. The mean distance between trees
350 (TLS_DISTANCE) accounted for 55% and 48% of the explained variation in MFA and
351 MOE, respectively. Adding TLS metrics to the “STEM+CROWN” models reduced the
352 AICc scores for estimating wood density and coarseness. The “STEM+CROWN+TLS”
353 models provided substantial support for estimating coarseness ($\Delta_i=1$; $w_{\text{BEST}}/w_i=1$) but no
354 support for estimating basic wood density ($\Delta_i=13$; $w_{\text{BEST}}/w_i=773$). The “TLS” and
355 “STEM+CROWN+TLS” models were the same for fiber length, MFA, and MOE, with
356 only TLS metrics retained in the best models. Adding TLS metrics into the
357 “STEM+CROWN+CORE” models was more conclusive. The
358 “STEM+CROWN+CORE+TLS” models were indeed the top-ranking models for
359 estimating coarseness, fiber length, MFA, and MOE. The TLS metrics accounting for
360 37%, 68%, 42%, and 61% of the explained variation in coarseness, fiber length, MFA,
361 and MOE, respectively. The “STEM+CROWN+CORE” and
362 “STEM+CROWN+CORE+TLS” models were the same for wood density as no TLS
363 metrics were retained in the best models.

364 Discussion

365 The contribution of TLS to the estimation of wood fiber attributes at the tree level was
366 demonstrated in black spruce. The “TLS” models, developed using only TLS metrics,
367 accounted for 47%, 33%, 51%, 44%, and 52% of variance in wood density, coarseness,
368 fiber length, MFA, and MOE, respectively, with root mean square error (RMSE) and
369 normalized RMSE values of 46 kg/m³ (17%), 37 µg/m (17%), 0.20 mm (16%),
370 3.5° (15%), 2.3 GPa (15%). These “TLS” models were the second top-ranking models for
371 estimating fiber length, MFA, and MOE. In addition, at least one TLS metric was
372 retained in the top-ranking models for estimating coarseness, fiber length, MFA, and
373 MOE. The contribution of TLS was less obvious for estimating wood density when the
374 models included core measurements. However, in the field, it is only possible to measure
375 the crown and collect increment cores on a few trees within a plot. An inventory using
376 only TLS data would therefore be preferred over conventional inventories to predict the
377 fiber attributes at the tree level if TLS data could be available for all trees within a plot.
378 The “TLS” models were indeed always more parsimonious than “STEM” models for
379 estimating the attributes of wood fiber. The TLS models were also more parsimonious
380 than the “STEM+CROWN+CORE” models for estimating fiber length, MFA, and MOE.

381 As the top-ranking models included core measurements, it was not surprising that TLS
382 metrics added little additional information, particularly for wood density. The core
383 measurements take into account the past growth of the tree and the level of maturity of
384 the cambium. The first growth rings from the pith form the juvenile wood, which has
385 inferior physical and mechanical properties than those found in the mature wood of the

386 same tree (Panshin and de Zeeuw 1980). The maturity of the cambium at a given height is
387 thus related to the number of rings, which turned out to be one of the most important
388 covariates in our study. These results were consistent with previously published results
389 for black spruce wood properties (Alteyrac et al. 2006; Giroud et al. 2016; Pokharel et al.
390 2014). A negative influence of the radial growth on the wood fiber attributes at breast
391 height was also observed in the current study. This inverse relationship is known in black
392 spruce, particularly for wood density (Giroud et al. 2016; Groot and Luther 2015). Ring
393 width is indeed negatively related to the proportion of latewood in softwoods (Panshin
394 and de Zeeuw 1980). A large part of the variation in trees may also be due to cambium
395 responses to different growth stresses over the life of a tree, such as drought or wind
396 stress, which directly influence the MFA and other wood properties (Donaldson 2008).

397 Contrary to our expectations, detailed crown metrics derived from TLS point clouds were
398 not more related with wood fiber attributes than field crown metrics. The influence of
399 canopy competition indices was also limited. However, some biological interpretation
400 can be done. Based on the 3D reconstruction of the crown, we confirmed, for example,
401 that trees with large crowns produced less dense wood as suggested by Larson (1969).
402 Wood fiber attributes were also positively influenced by the base of live crown. As the
403 tree crown rises with time, the cambium at a given height becomes less subject to direct
404 influence of the crown, and mature wood is formed (Panshin and de Zeeuw 1980).

405 However, manual extraction of this metric from the TLS point cloud has limitations. The
406 base of live crowns measured in the field seemed more accurate, as shown by the higher
407 correlations obtained with wood fiber attributes. An automatic procedure to extract this
408 metric could improve the accuracy and possibly the overall contribution of TLS. The

409 sampling method may partly explain the limited influence of crown metrics. Indeed,
410 wood fiber attributes were measured from pith to bark at breast height, but these
411 attributes also vary longitudinally within a tree (Panshin and de Zeeuw 1980). Whole-tree
412 estimates could be used to better characterize the relationships with crown metrics, or
413 other tree-level metrics, and potentially improve the predictive ability of the models.
414 Breast-height estimates are nevertheless considered moderate to good predictors for the
415 whole tree (Evans et al. 2000).

416 Competition metrics derived from TLS were also interesting covariates for assessing
417 wood fiber attributes. As expected, trees suppressed by their immediate neighbors had
418 better physical and mechanical properties (Johansson 1993; Yang and Hazenberg 1994).
419 Better wood properties were also found in trees growing in an immediate environment
420 characterized by an irregular forest structure. Standard deviation and rumple index of the
421 local canopy height models were indeed positively and strongly correlated with the age of
422 target trees ($r \sim 0.7$; results not shown). Although there has been limited study of the
423 influence of terrain on wood attributes because of the difficulty in accurately measuring
424 terrain features, we found that trees growing on sloping ground produced wood with
425 lower physical and mechanical properties. These results were unexpected because
426 compression wood is usually observed in such growth conditions. However, the
427 variability of the mean slope was relatively limited in the current study.

428 **Conclusion**

429 The contribution of TLS for estimating wood fiber attributes at the tree level was
430 investigated for black spruce trees growing in Newfoundland, Canada. This study
431 demonstrated that more accurate characterization of the tree, its crown, and its immediate
432 environment using TLS metrics improved the predictive ability of the models for
433 estimating most wood fiber attributes of black spruce. An inventory using only TLS data
434 would be preferred over conventional inventories to predict fiber attributes at the tree
435 level, particularly if TLS data were available for all trees in a plot. Terrestrial laser
436 scanning provides information beyond what is typically available from conventional
437 inventories, however, there remain some issues to address for operational use, such as
438 reducing the effects of occlusion and automating processes to extract metrics at the tree
439 level. Nonetheless, TLS data acquisition and processing is becoming more and more
440 efficient, suggesting great potential for application in forestry in the coming years.
441 Finally, this study was developed as a proof-of-concept to evaluate the contribution of
442 TLS for estimating wood fiber attributes at the tree level. More sampled trees and sites
443 would be required to develop models that could be generalized to any black spruce site.

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457 **References**

- 458 Alemdag, I.S. 1984. Wood density variation of 28 tree species from Ontario. Natural
459 Resources Canada, Canadian Forest Service, Petawawa, ON. Information Report
460 PI-X-45F.
- 461 Alteyrac, J., Cloutier, A., and Zhang, S.Y. 2006. Characterization of juvenile wood to
462 mature wood transition age in black spruce (*Picea mariana* (Mill.) B.S.P.) at
463 different stand densities and sampling heights. *Wood Sci. Technol.* **40**(2):
464 124–138.
- 465 Blanchette, D., Fournier, R.A., Luther, J.E., and Côté, J.F. 2015. Predicting wood fiber
466 attributes using local-scale metrics from terrestrial LiDAR data: a case study of
467 Newfoundland conifer species. *For. Ecol. Manage.* **347**: 116–129.
- 468 Burnham, K.P., and Anderson, D.R. 2003. Model selection and multimodel inference: a
469 practical information-theoretic approach. Springer Science & Business Media,
470 New York.
- 471 Clark, P.J., and Evans, F.C. 1954. Distance to nearest neighbor as a measure of spatial
472 relationships in populations. *Ecology* **35**(4): 445–453.
- 473 Defo, M., Duchesne, I., and Stewart, J. 2015. A review of the current state of wood
474 quality modelling and decision support systems in Canada. Natural Resources
475 Canada, Canadian Forest Service – Canadian Wood Fibre Centre. Laurentian
476 Forestry Centre, Québec, QC. Information Report FI-X-012.
- 477 Donaldson, L. 2008. Microfibril angle: measurement, variation and relationships – a
478 review. *IAWA J.* **29**(4): 345–386.

- 479 Evans, R. 1994. Rapid measurement of the transverse dimensions of tracheids in radial
480 wood sections from *Pinus radiata*. *Holzforschung* **48**(2): 168–172.
- 481 Evans, R. 2006. Wood stiffness by X-ray diffractometry. Chapter 11. *In* :
482 Characterization of the cellulosic cell wall. *Edited by* Stokke D.D. and L. H.
483 Groom. Proceedings of a workshop cosponsored by the USDA Forest Service -
484 Southern Research Station, the Society of Wood Science and Technology, and
485 Iowa State University, Grand Lake, Colorado, USA, August 25–27 2003.
486 Blackwell Publishing, Hoboken, NJ. pp. 138–146.
- 487 Evans, R., Stringer S. and Kibblewhite R.P. 2000. Variation of microfibril angle, density
488 and fibre orientation in twenty-nine *Eucalyptus nitens* trees. *Appita J.* **53**(5): 450–
489 457.
- 490 Giroud, G., Bégin, J., Defo, M., and Ung, C.H. 2016. Ecogeographic variation in black
491 spruce wood properties across Quebec's boreal forest. *For. Ecol. Manage.* **378**:
492 131–143.
- 493 Giroud, G., Bégin, J., Defo, M., and Ung, C.H. 2017. Regional variation in wood density
494 and modulus of elasticity of Quebec's main boreal tree species. *For. Ecol. Manage.*
495 **400**: 289–299.
- 496 Government of Newfoundland and Labrador. 2015. Newfoundland and Labrador Wood
497 Products Industry. 2014 Summary. 2015 Issue. Forestry & Agrifoods Agency,
498 Corner Brook, NL. Available from
499 http://www.faa.gov.nl.ca/publications/pdf/Wood_Prod_Ind_2014.pdf [accessed
500 2018-08-07].

- 501 Government of Newfoundland and Labrador. 2018a. Forest Products Industry [online].
502 Available from <http://www.faa.gov.nl.ca/forestry/support/services.html> [accessed
503 2018-08-07].
- 504 Government of Newfoundland and Labrador. 2018b. Forest Types [online]. Available
505 from http://www.faa.gov.nl.ca/forestry/our_forest/forest_types.html [accessed
506 2018-08-07].
- 507 Groot, A., and Luther, J.E. 2015. Hierarchical analysis of black spruce and balsam fir wood
508 density in Newfoundland. *Can. J. For. Res.* **45**(7): 805–816.
- 509 Groot, A., Cortini, F., and Wulder, M.A. 2015. Crown-fibre attribute relationships for
510 enhanced forest inventory: Progress and prospects. *For. Chron.* **91**(3): 266–279.
- 511 Huang, H., Gong, P., Cheng, X., Clinton, N., Cao, C., Ni, W., Li, Z., and Wang, L. 2009.
512 Forest structural parameter extraction using terrestrial LiDAR. *In Proceedings of*
513 *SilviLaser 2009: 9th international conference on LiDAR applications for assessing*
514 *forest ecosystems*, Texas A&M University, Austin, TX, October 14–16, 2009.
- 515 Johansson, K. 1993. Influence of initial spacing and tree class on the basic density of *Picea*
516 *abies*. *Scand. J. Forest Res.* **8**(1–4): 18–27.
- 517 Kane, V.R., McGaughey, R.J., Bakker, J.D., Gersonde, R.F., Lutz, J.A., and Franklin, J.F.
518 2010. Comparisons between field-and LiDAR-based measures of stand structural
519 complexity. *Can. J. For. Res.* **40**(4): 761–773.
- 520 Lafarge, T., and Pateiro-Lopez, B. 2017. R package “Alphashape3d”. Implementation of
521 the 3D alpha-shape for the reconstruction of 3D sets from a point cloud. Available

- 522 from <https://cran.r-project.org/web/packages/alphashape3d/alphashape3d.pdf>
523 [accessed 2018-08-07].
- 524 Larson P.R. 1969. Wood formation and the concept of wood quality. Yale University
525 School of Forestry, New Haven, CT. Bull. No.74.
- 526 Lecigne, B., Delagrangé, S., and Messier, C. 2015. R package “VoxR”. Metrics
527 extraction of trees from T-LiDAR data. Available from [https://cran.r-](https://cran.r-project.org/web/packages/VoxR/VoxR.pdf)
528 [project.org/web/packages/VoxR/VoxR.pdf](https://cran.r-project.org/web/packages/VoxR/VoxR.pdf) [accessed 2018-08-07].
- 529 Lessard, E., Fournier, R.A., Luther, J.E., Mazerolle, M.J., and van Lier, O.R. 2014.
530 Modeling wood fiber attributes using forest inventory and environmental data for
531 Newfoundland’s boreal forest. *For. Ecol. Manage.* **313**: 307–318.
- 532 Li, B., Li, H., Zha, Q., Bandekar, R., Alsaggaf, A., and Ni, Y. 2011. Review: effects of
533 wood quality and refining process on TMP pulp and paper quality. *BioResources*
534 **6**(3): 3569–3584.
- 535 Luther, J.E., Skinner, R., Fournier, R.A., van Lier, O.R., Bowers, W.W., Côté, J.-F.,
536 Hopkinson, C., and Moulton, T. 2014. Predicting wood quantity and quality
537 attributes of balsam fir and black spruce using airborne laser scanner data. *Forestry*
538 **87**: 313–326.
- 539 Martin-Ducup, O., Robert, S., and Fournier, R.A. 2016. Response of sugar maple (*Acer*
540 *saccharum*, Marsh.) tree crown structure to competition in pure versus mixed
541 stands. *For. Ecol. Manage.* **374**: 20–32.

- 542 Nakagawa, S., and Schielzeth, H. 2013. A general and simple method for obtaining R^2
543 from generalized linear mixed-effects models. *Methods Ecol. Evol.* **4**(2): 133–
544 142.
- 545 Natural Resources Canada. 2010. The principal attributes of Canadian wood fibre.
546 Natural Resources Canada, Canadian Forest Service – Canadian Wood Fibre
547 Centre. Ottawa, ON.
- 548 Othmani, A., Piboule, A., Krebs, M., Stolz, C., and Voon, L.L.Y. 2011. Towards
549 automated and operational forest inventories with T-Lidar. *In Proceedings of*
550 *SilviLaser 2011: 11th international Conference on LiDAR applications for*
551 *assessing forest ecosystems*, University of Tasmania, Hobart, Australia. October
552 16–20, 2011. Available from
553 http://www.iufro.org/download/file/8239/5065/40205-silvilaser2011_pdf
554 [accessed 2018-08-07]. pp. 465–473.
- 555 Panshin, A.J., and de Zeeuw, C. 1980. Textbook of wood technology. Structure,
556 identification, properties, and uses of the commercial woods of the United States
557 and Canada. 4th edition. McGraw-Hill Book Company, New York. 722 p.
- 558 Pokharel, B., Dech, J.P., Groot, A., and Pitt, D. 2014. Ecosite-based predictive modeling
559 of black spruce (*Picea mariana*) wood quality attributes in boreal Ontario. *Can. J.*
560 *For. Res.* **44**(5): 465–475.
- 561 Pokharel, B., Groot, A., Pitt, D.G., Woods, M., and Dech, J.P. 2016. Predictive modeling
562 of black spruce (*Picea mariana* (Mill.) BSP) wood density using stand structure

- 563 variables derived from airborne LiDAR data in boreal forests of Ontario. *Forests*
564 **7**(12): 311.
- 565 R Core Team. 2018. R: A Language and Environment for Statistical Computing. R
566 Foundation for Statistical Computing, Vienna, Austria. Available from
567 <http://www.R-project.org> [accessed 2018-08-07].
- 568 Robertson, G., Olson, J., Allen, P., Chan, B., and Seth, R. 1999. Measurement of fiber
569 length, coarseness, and shape with the fiber quality analyzer. *Tappi J.* **82**: 93–98.
- 570 Siau, J.F. 1995. Wood: influence of moisture on physical properties. Dept. of Wood
571 Science and Forest Products, Virginia Polytechnic Institute and State University,
572 Blacksburg, VA.
- 573 Yang, K.C., and Hazenberg, G. 1994. Impact of spacing on tracheid length, relative density,
574 and growth-rate of juvenile wood and mature wood in *Picea mariana*. *Can. J. For.*
575 *Res.* **24**(5): 996–1007.

576 **Table captions**

577 **Table 1.** Site characteristics and descriptive statistics of wood fiber attributes.

578 **Table 2.** Descriptive statistics of wood fiber attributes, field, and TLS metrics ($n = 69$
579 visible target trees). The different groups of covariates are shown (“CORE”, “STEM”,
580 “CROWN”, and “TLS”).

581 **Table 3.** Pearson’s correlation for wood fiber attributes, field, and TLS metrics. Highly
582 significant correlations ($P < 0.001$) are shown in bold.

583 **Table 4.** Top-ranking models of wood fiber attributes. Differences in AICc (Δ_i), AICc
584 weight (w_i), pseudo-R², and RMSE are provided. Signs of parameter coefficients (S1, S2,
585 S3) and percentages of variance explained by the model (P1, P2, P3) are shown for each
586 covariate (V1, V2, V3). TLS metrics are shown in bold.

587 **Table 1.** Site characteristics and descriptive statistics of wood fiber attributes

Site ID	TLS visible target tree count	Latitude N	Longitude W	Elevation (m)	Slope (%)	Black spruce (%)	Tree age		BD (kg/m ³)		COA (µg/m)		FL (mm)		MFA (°)		MOE (GPa)	
							mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.
18900805	4	49°01"10	54°09"40	98	0	98	70	10%	590.9	7%	401.9	11%	2.4	7%	12.6	22%	17.2	16%
18901205	6	48°59"40	53°58"17	76	6	100	32	8%	538.4	10%	358.3	6%	2.0	7%	16.0	25%	13.8	14%
18905502	3	48°18"09	53°44"22	110	5	69	23	9%	450.2	3%	305.4	11%	1.9	6%	18.5	13%	9.9	17%
19200416	3	49°34"36	57°03"20	130	6	69	48	9%	493.3	5%	318.0	5%	2.0	7%	21.1	27%	10.2	21%
19203116	3	49°43"58	57°16"05	340	15	77	28	5%	443.4	4%	313.2	10%	1.8	6%	27.3	19%	7.0	23%
19400404	3	48°33"12	54°56"28	232	0	91	97	30%	561.6	1%	384.5	7%	2.2	3%	16.0	10%	13.9	5%
19400504	7	48°31"13	54°57"37	220	0	86	120	22%	621.2	6%	383.0	9%	2.1	10%	12.8	28%	17.2	10%
19400706	6	48°51"25	54°35"45	189	3	98	71	20%	554.5	4%	395.7	5%	2.2	8%	12.8	17%	15.4	7%
19401411	5	48°48"37	56°00"44	198	5	94	86	6%	512.3	9%	375.9	9%	2.4	7%	11.4	18%	15.4	17%
19401611	4	48°35"38	55°57"07	192	12	82	102	11%	546.9	6%	404.0	7%	2.7	3%	14.0	25%	14.9	14%
19401911	4	48°35"25	55°34"14	175	3	97	148	11%	599.6	12%	423.4	11%	2.7	7%	10.4	19%	18.2	7%
19500110	3	49°04"55	55°57"10	138	0	99	67	7%	572.5	17%	411.9	17%	2.4	7%	12.0	8%	16.5	21%
19500508	6	49°11"25	54°39"20	61	0	100	75	10%	530.6	7%	361.2	9%	2.3	9%	17.6	15%	12.7	18%
19501112	9	48°44"52	56°45"54	158	5	95	78	14%	594.4	8%	410.9	8%	2.4	7%	15.8	23%	14.9	16%
19501309	1	49°53"14	56°13"02	80	5	78	54	-	465.8	-	344.2	-	2.1	-	18.4	-	10.7	-
19502309	2	49°24"25	55°38"24	131	30	37	73	4%	595.4	2%	433.8	8%	2.7	5%	11.8	19%	17.3	12%

588

590 **Table 2.** Descriptive statistics of wood fiber attributes, field, and TLS metrics ($n = 69$ visible target trees). The different groups of
591 covariates are shown (“CORE”, “STEM”, “CROWN”, and “TLS”)

Variable	Description	Abbreviation	mean	s.d.	min.	max.	CORE	STEM	CROWN	TLS
Core-level	response	Basic wood density (kg/m ³)	BD	553.2	62.9	421.2	699.1			
	response	Coarseness (μg/m)	COA	380.8	45.6	267.9	491.4			
	response	Fiber length (mm)	FL	2.3	0.3	1.7	2.9			
	response	Microfibril angle (°)	MFA	15.1	4.7	8.8	32.2			
	response	Modulus of elasticity (GPa)	MOE	14.5	3.3	5.8	20.8			
	field data	Ring number	RN	77.0	34.1	21.0	165.0	X		
	field data	Log transformation of ring number	RNLN	4.2	0.5	3.0	5.1	X		
	field data	Ring width (mm)	RW	0.9	0.6	0.3	3.0	X		
Tree-level	field data	Diameter at breast height (cm)	DBH	14.2	3.7	8.6	24.5		X	
	field data	Tree height (m)	TH	11.1	2.4	6.8	16.3		X	
	field data	Slenderness, ratio of tree height to DBH (m/cm)	HD	0.8	0.1	0.5	1.1		X	
	field data	Basal area of larger trees (m ² /ha)	BAL	18.4	11.3	0.5	52.9		X	
	field data	Base of live crown (m)	CR_BLC	6.4	2.4	1.0	10.5			X
	field data	Crown length (m)	CR_LGT	4.6	2.1	0.4	9.7			X
	TLS data	Diameter at breast height (cm)	TLS_DBH	15.4	3.6	9.4	25.2			X
	TLS data	Tree height (m)	TLS_TH	11.5	2.4	6.9	17.0			X
	TLS data	Slenderness, ratio of tree height to DBH (m/cm)	TLS_HD	0.8	0.1	0.4	1.1			X
	TLS data	Base of live crown (m)	TLS_CR_BLC	4.6	2.4	0.6	9.7			X
	TLS data	Crown length (m)	TLS_CR_LGT	6.9	2.7	2.8	13.4			X
	TLS data	Crown surface area (m ²)	TLS_CR_SA	44.6	29.8	11.4	150.3			X
	TLS data	Crown density (%)	TLS_CR_DEN	20.7	6.3	9.7	39.5			X
	TLS data	Crown volume (m ³)	TLS_CR_VOL	11.9	10.1	1.8	52.2			X
	TLS data	Canopy pressure index	CPI	3.7	1.6	0.8	9.8			X
	TLS data	Canopy heterogeneity index	CHI	1.5	0.2	0.7	1.8			X
	TLS data	Canopy density index	CDI	0.23	0.14	0.00	0.55			X
	TLS data	Canopy height model - mean (m)	CHM_MEAN	8.2	1.9	4.3	11.9			X
	TLS data	Canopy height model - standard deviation (m)	CHM_STD	2.1	0.8	0.9	3.5			X
	TLS data	Canopy height model - volume to area ratio (m ³ /m ²)	CHM_RATIO	367.1	199.3	85.1	823.9			X
	TLS data	Canopy height model - rumple index (unitless)	CHM_RUMPLE	4.6	1.2	2.7	7.4			X
	TLS data	Digital elevation model - standard deviation (m)	DEM_EL_STD	0.2	0.1	0.0	0.4			X
	TLS data	Digital elevation model - relative difference (unitless)	DEM_EL_DIF	0.7	0.4	0.2	1.8			X
	TLS data	Digital elevation model - rumple index (unitless)	DEM_EL_RUMPLE	1.01	0.01	1.00	1.03			X
	TLS data	Digital elevation model - mean slope (°)	DEM_SL_MEAN	5.0	2.9	1.4	12.7			X
	TLS data	Digital elevation model - standard deviation of the slope (°)	DEM_SL_STD	1.7	0.8	0.8	4.9			X
	TLS data	Nearest neighbor ratio (m/m, therefore unitless)	TLS_RATIO	1.2	0.3	0.6	2.0			X
	TLS data	Mean distance between trees (m)	TLS_DISTANCE	1.0	0.4	0.5	2.5			X

593 **Table 3.** Pearson's correlation for wood fiber attributes, field, and TLS metrics. Highly significant correlations ($P < 0.001$) are shown
 594 in bold

Variable		Description	BD	COA	FL	MFA	MOE
Core-level	response	Basic wood density (kg/m ³)	1.00				
	response	Coarseness (µg/m)	0.65	1.00			
	response	Fiber length (mm)	0.29	0.61	1.00		
	response	Microfibril angle (°)	-0.38	-0.50	-0.58	1.00	
	response	Modulus of elasticity (GPa)	0.73	0.67	0.55	-0.89	1.00
	field data	Ring number	0.47	0.47	0.56	-0.54	0.59
	field data	Log transformation of ring number	0.53	0.53	0.63	-0.55	0.62
field data	Ring width (mm)	-0.70	-0.58	-0.56	0.56	-0.70	
Tree-level	field data	Diameter at breast height (cm)	-0.39	n.s.	0.26	n.s.	n.s.
	field data	Tree height (m)	n.s.	n.s.	0.50	-0.32	n.s.
	field data	Slenderness, ratio of tree height to DBH (m/cm)	0.58	0.34	n.s.	-0.27	0.44
	field data	Basal area of larger trees (m ² /ha)	0.32	n.s.	n.s.	n.s.	n.s.
	field data	Base of live crown (m)	0.36	0.46	0.46	-0.41	0.43
	field data	Crown length (m)	-0.34	n.s.	n.s.	n.s.	n.s.
	TLS data	Base of live crown (m)	n.s.	0.29	n.s.	-0.28	0.24
	TLS data	Crown length (m)	n.s.	n.s.	0.33	n.s.	n.s.
	TLS data	Crown density (%)	n.s.	n.s.	-0.34	n.s.	n.s.
	TLS data	Crown volume (m ³)	-0.42	n.s.	n.s.	n.s.	-0.28
	TLS data	Canopy pressure index	0.39	n.s.	n.s.	n.s.	0.31
	TLS data	Canopy heterogeneity index	0.41	0.32	n.s.	-0.42	0.43
	TLS data	Canopy density index	0.35	n.s.	n.s.	n.s.	0.29
	TLS data	Canopy height model - standard deviation (m)	n.s.	0.26	0.50	-0.32	0.34
	TLS data	Canopy height model - rumple index (unitless)	0.26	0.29	0.50	-0.33	0.37
	TLS data	Digital elevation model - rumple index (unitless)	-0.44	-0.31	n.s.	0.38	-0.43
	TLS data	Digital elevation model - mean slope (°)	-0.47	-0.33	-0.24	0.35	-0.43
	TLS data	Nearest neighbor ratio (m/m, therefore unitless)	-0.37	-0.49	-0.65	0.51	-0.54
	TLS data	Mean distance between trees (m)	-0.41	-0.47	-0.38	0.49	-0.52

595

596

597 **Table 4.** Top-ranking models of wood fiber attributes. Differences in AICc (Δ_i), AICc weight (w_i), pseudo- R^2 , and RMSE are provided.
 598 Signs of parameter coefficients (S1, S2, S3) and percentages of variance explained by the model (P1, P2, P3) are shown for each
 599 covariate (V1, V2, V3). TLS metrics are shown in bold

Wood fiber attribute	Model set	AIC _c	Δ_i	w_i	R^2	RMSE	V1	S1	P1	V2	S2	P2	V3	S3	P3
Basic wood density (kg/m ³)	STEM+CROWN+CORE	712	0	0.500	0.61	39.5	RNLN	+	46%	HD	+	35%	TH	-	19%
	STEM+CROWN+CORE+TLS	712	0	0.500	0.61	39.5	RNLN	+	46%	HD	+	35%	TH	-	19%
	STEM+CROWN+TLS	725	13	0.001	0.54	42.8	DBHLN	-	47%	CHM_RUMPLE	+	35%	DEM_SL_MEAN	-	18%
	CORE	728	16	0.000	0.48	45.3	RW	-	100%						
	STEM+CROWN	731	18	0.000	0.36	50.3	DBH	-	44%	CR_BLC	+	33%	CR_LGT	+	22%
	TLS	733	21	0.000	0.47	46.0	TLS_CR_VOL	-	48%	DEM_SL_MEAN	-	28%	TLS_CR_LGT	+	24%
	STEM	734	22	0.000	0.33	51.5	HD	+	100%						
Coarseness ($\mu\text{g}/\text{m}$)	STEM+CROWN+CORE+TLS	698	0	0.403	0.37	36.2	RNLN	+	63%	TLS_DISTANCE	-	37%			
	STEM+CROWN+TLS	698	1	0.284	0.38	35.8	TLS_CR_DEN	-	40%	TLS_DISTANCE	-	35%	CR_BLC	+	25%
	STEM+CROWN+CORE	700	2	0.141	0.33	37.4	RW	-	100%						
	CORE	700	2	0.141	0.33	37.4	RW	-	100%						
	STEM+CROWN	704	6	0.016	0.13	42.4	CR_BLC	+	54%	CR_LGT	+	46%			
	TLS	705	7	0.013	0.33	37.4	CHM_RUMPLE	+	56%	TLS_CR_DEN	+	29%	CPI	+	14%
	STEM	710	12	0.001	0.04	44.6	TH	+	100%						
Fiber length (mm)	STEM+CROWN+CORE+TLS	-25	0	0.760	0.47	0.21	TLS_CR_VOL	+	45%	RW	-	32%	CHM_MEAN	+	23%
	TLS	-21	4	0.093	0.51	0.20	CHM_STD	+	67%	TLS_CR_DEN	+	21%	TLS_DISTANCE	+	12%
	STEM+CROWN+TLS	-21	4	0.093	0.51	0.20	CHM_STD	+	67%	TLS_CR_DEN	+	21%	TLS_DISTANCE	+	12%
	STEM+CROWN+CORE	-19	6	0.036	0.42	0.22	RW	-	61%	DBH	+	39%			
	CORE	-17	8	0.015	0.39	0.22	RNLN	+	100%						
	STEM+CROWN	-13	12	0.002	0.24	0.25	TH	+	100%						
	STEM	-13	12	0.002	0.24	0.25	TH	+	100%						
Microfibril angle (°)	STEM+CROWN+CORE+TLS	375	0	0.431	0.42	3.6	RN	-	58%	TLS_DISTANCE	+	42%			
	TLS	376	1	0.262	0.44	3.5	TLS_DISTANCE	+	55%	CHM_STD	-	25%	DEM_EL_RUMPLE	+	21%
	STEM+CROWN+TLS	376	1	0.262	0.44	3.5	TLS_DISTANCE	+	55%	CHM_STD	-	25%	DEM_EL_RUMPLE	+	21%
	STEM+CROWN+CORE	381	6	0.023	0.30	3.9	RNLN	-	100%						
	CORE	381	6	0.023	0.30	3.9	RNLN	-	100%						
	STEM+CROWN	390	15	0.000	0.15	4.3	CR_BLC	-	65%	CR_LGT	-	35%			
	STEM	391	16	0.000	0.09	4.5	TH	-	100%						
Modulus of elasticity (GPa)	STEM+CROWN+CORE+TLS	316	0	0.424	0.52	2.3	RW	-	39%	DEM_EL_RUMPLE	-	31%	TLS_RATIO	-	29%
	TLS	318	2	0.172	0.52	2.3	TLS_DISTANCE	-	48%	CHM_RUMPLE	+	30%	DEM_EL_RUMPLE	-	22%
	STEM+CROWN+TLS	318	2	0.172	0.52	2.3	TLS_DISTANCE	-	48%	CHM_RUMPLE	+	30%	DEM_EL_RUMPLE	-	22%
	STEM+CROWN+CORE	319	3	0.116	0.48	2.3	RW	-	100%						
	CORE	319	3	0.116	0.48	2.3	RW	-	100%						
	STEM+CROWN	330	14	0.000	0.22	2.9	CR_BLC	+	51%	CR_LGT	+	31%	DBH	-	18%
	STEM	333	17	0.000	0.20	2.9	TH	+	59%	DBH	-	41%			

601 **Figure captions**

602 **Figure 1.** Sampling configuration for the TLS data acquisition (Blanchette et al. 2015).
603 The term “sampled fiber tree” refers to a target tree. The term “area of interest” refers to a
604 TLS scene including all the target trees.

605 **Figure 2.** TLS data processing: (A) extraction of the scene using an upside-down cone
606 placed at the tree base with a 30° opening angle. The cylinder diameter was estimated as a
607 function of the highest point of the canopy; (B and C) extraction of the target tree using a
608 semi-automatic procedure in Computree software; (D) reconstruction of the crown using
609 the “alphashape3d” R package; (E) extraction of the immediate vegetation, surrounding
610 each target tree, using an upside-down cone placed at the crown base with a 30° opening
611 angle.

Draft

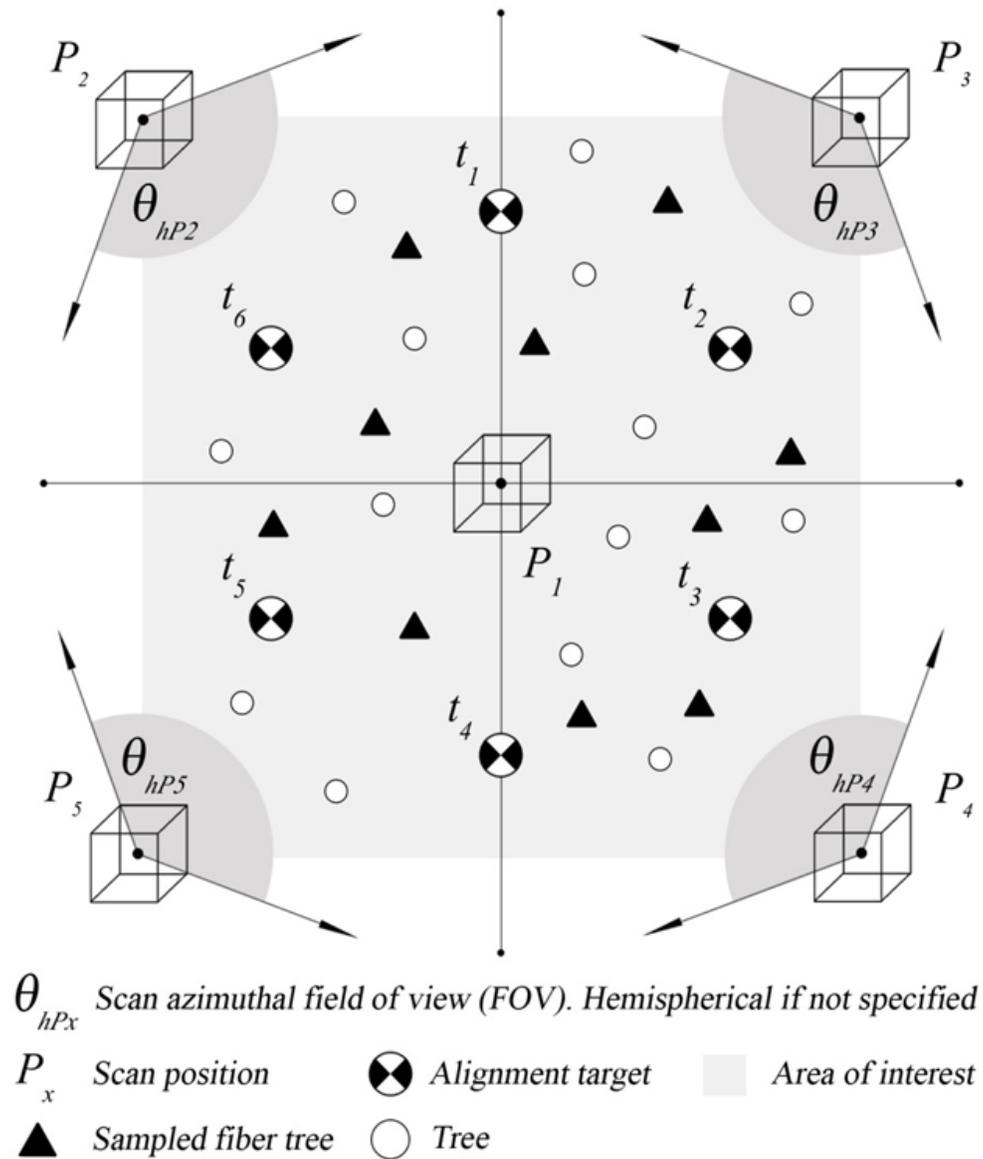


Figure 1. Sampling configuration for the TLS data acquisition (Blanchette et al. 2015). The term "sampled fiber tree" refers to a target tree. The term "area of interest" refers to a TLS scene including all the target trees.

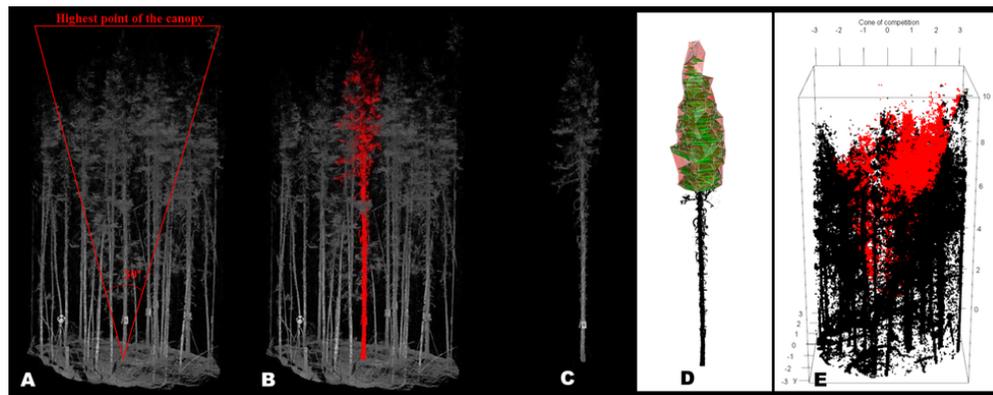


Figure 2. TLS data processing: (A) extraction of the scene using an upside-down cone placed at the tree base with a 30° opening angle. The cylinder diameter was estimated as a function of the highest point of the canopy; (B and C) extraction of the target tree using a semi-automatic procedure in Computree software; (D) reconstruction of the crown using the "alphashape3d" R package; (E) extraction of the immediate vegetation, surrounding each target tree, using an upside-down cone placed at the crown base with a 30° opening angle.

83x33mm (300 x 300 DPI)