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The influence of crown and stem characteristics on timber quality in softwoods

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ABSTRACT

The relationships between several crown and tree properties and timber quality were examined on three softwood species: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Norway spruce (*Picea abies* (L.) H. Karst) and Sitka spruce (*Picea sitchensis* (Bong.) Carr). Crown and stem characteristics were collected on 487 standing trees, and their acoustic velocity measured using a stress-wave device. Of the trees measured, 60 were chosen for further testing, stratified by crown social class and cut into structural sized boards (N = 1342). Each board was assessed with regard to knots using a grading X-ray machine, after which all boards were destructively tested in four-point bending and their mechanical properties (elastic modulus, bending strength and density) evaluated. To exclude the effect of branchiness across the crown social classes, mechanical properties were also examined on small clear samples cut from the undamaged section of the tested boards, a total of 1303 specimens were tested destructively in bending. Multi-level models based on Bayesian data analysis were used to evaluate the relationships between recorded characteristics, acoustic velocities and mechanical properties. Considerable differences in acoustic velocities were found between crown social classes, with suppressed trees having the highest velocities. This trend was also confirmed in mechanical properties of structural-sized boards and small clear specimens, suggesting that branchiness is not the primary cause of differences. Results indicate that slenderness affects both tree stiffness and the properties of sawn timber differently across the crown social classes. The relationship is negative in suppressed trees (increasing slenderness leads to a decrease in velocity or mechanical properties) and positive in dominant and co-dominant trees. The effect of crown projection area on either tree acoustic velocity or mechanical properties differs between social classes. In general, it was found to be positive, therefore an increase in crown projection area leads to an increase in either tree acoustic velocity or wood properties of timber. This trend is more evident in sawn timber than in acoustic velocities. The effects appear to be species dependant. No evidence was found of the effect of crown ratio, crown eccentricity or crown roundness on either the examined wood properties or acoustic velocities. Results confirm that there is a link between crown/stem development and timber quality. They indicate that in order to increase the overall quality of timber produced, the proportions of crown social classes in final stand composition should be adjusted with thinning.

1. Introduction

Wood quality can be defined as the suitability of a certain wood product for a specific purpose and is as such a very flexible term. In structural-sized sawn timber the definition reflects the previous statement, as the three strength grade determining properties limit the appropriate end use by sorting the timber into strength classes by modulus of elasticity (MOE), bending strength (also known as modulus of rupture, MOR) and clear wood density as per the European strength classification system defined in EN 338 (CEN, 2016). As the three properties are affected by a variety of environmental factors, studying each factor individually can lead to premature conclusions due to the many interactions found in ecosystems. Only by looking at them collectively one can examine the size and the direction of the effect for possible inferences. In forest ecosystems, a tree crown is responsible for photosynthesis and as such impacts growth of all other parts of the organism. It represents the sum of all past and present environmental influences and is as such a good proxy for assessing an individual tree.

Crowns can be described with a variety of metrics, usually aimed at describing an individual crown in relation to others or as a standalone

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subject. When describing the social status of the tree, the crown of the subject tree is evaluated in relation to crowns of neighbouring trees. One of the first crown class classifications was proposed by Kraft in 1884; separating trees into predominant, dominant, co-dominant, dominated and overtopped (also referred to as inferior) categories (Assmann, 1970). A simplified version using only three classes is also in use, distinguishing dominant, co-dominant and suppressed trees. It is also worth noting that the terminology with regard to social class or status is somewhat vague, as researchers sometimes separate the tree into social classes according to their relative diameter at breast height. Both classification systems are not interchangeable, as stem diameter does not necessarily correlate with crown social position relative to neighbouring crowns. Separation of trees into social classes by diameter is usually done *post hoc* on completed measurements. Crown classification has to be done *in situ* and is probably more subjective particularly with borderline subjects, where the assigned social class is determined partly by the limits of the human eye.

The exact nature of the relationship between crown development and wood properties is not yet fully understood. The vascular system was shown to be intimately related to the development and function of the foliar organs (Larson, 1969). Several possible mechanisms were provided by Larson (1969), where he partly explained the changes in wood properties in relation to the tree crown with changing auxin gradients along the stem. Tracheid radial diameter appears to be proportionally related to auxin changes in the stem. Another factor influencing wood formation is mechanical loading of the crown, which in turn causes a redistribution of growth favouring the region of higher stress, including changes to tracheid characteristics.

Several studies have looked at how the different properties of the crown influence the mechanical and physical properties of wood. Suppressed trees usually have higher wood density, however the differences are relatively small (Amarasekara and Denne, 2002; Deng et al., 2014; Johansson, 1993). It would appear that this relationship is somewhat dependant on the shade tolerance of the species studied, being reversed in more shade-intolerant species as shown in a study of seven subtropical species (Chen et al., 2017). In a study by Tsoumis and Panagiotidis (1980), the relationship between social status and wood density was found to be dependant on site quality, as was the interaction between social status and tracheid length. Co-dominant trees appeared to have the highest wood density across the studied site qualities, most differences were not statistically significant. Fajardo (2016) found significant differences in wood densities between suppressed and dominant trees in timber of two species of the *Nothofagus* genus. Differences were found in both heartwood and corewood wood densities. However, no differences were found when comparing standardised wood density (weighted mean of heartwood and sapwood densities by area proportions of each in stem cross-section) among dominant and suppressed trees. A Scandinavian study examined clear wood properties of Scots pine (*Pinus sylvestris* L.) in relation to silviculture and concluded that silviculture can have a evident effect on material properties, as it affects both crown properties and growth rate, which in turn directly affect the vascular cambium (Eriksson et al., 2006). The link between the crown development and wood density was also confirmed by Lindström (1996) and Simpson and Denne (1997). Branch development in Sitka spruce (*Picea sitchensis* (Bong.) Carr) was shown to be influenced by early re-spacing by Auty et al. (2012), indicating that wide re-spacing will have a negative effect on sawn timber quality. Similar results were found in Scots pine by (Fahlvik et al., 2005), where pre-commercial thinning affected both growth rate and the rate of naturally occurring pruning.

An increase in dominance has been shown to negatively impact the bending strength and the modulus of elasticity (Amarasekara and Denne, 2002). In black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenburg) bending strength and the elastic modulus increased with crown length (Liu et al., 2007). Stem shape was also confirmed as a good predictor of the overall wood quality. Both slenderness (the ratio of tree height to diameter at breast height) and taper were shown to have potential as predictors. (Lasserre et al., 2009; Lindström et al., 2009). Slenderness was found to have a positive relationship to stiffness in young loblolly pine (*Pinus taeda* L.) (Roth et al., 2007) and was found to have a sizable effect over the whole rotation period on board bending strength in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Poschenrieder et al., 2016). One of the frequently studied variables in relation to timber quality has been growth rate. While faster growth is commonly associated with decreasing wood density, the relation is species dependant and not necessarily negative. Studies reviewed by Zobel and van Buijtenen (1989) found no changes in density with increasing growth rate. A recent study carried out in Belgium on Douglas-fir discovered that while growth rate does not impact the characteristic values of grade-determining properties, and therefore the strength class of outerwood timber (mature wood), it does have an impact when looking at corewood timber (juvenile wood) (Henin et al., 2018).

Dunham and Cameron (2000) found that Sitka spruce trees with smaller crowns were more likely to snap and overturn due to wind or storm damage, whereas slenderness was not found to have an effect. Crowns of Scots pine and Norway spruce (*Picea abies* (L.) H. Karst) were shown to become more asymetrical with age with a different rate of change across species (Rautiainen et al., 2008). Diameter at breast height was shown to have a larger effect on crown projection area and live crown length than competition index or tree-species diversity (Forrester et al., 2017).

Several other factors can also have an effect on the mechanical properties, both directly and indirectly. Starting with stand formation, initial planting density (Aslezaeim, 2016; Johansson, 1993; Lasserre et al., 2005; Rais et al., 2014; Simic et al., 2017) or the genetic makeup (Dungey et al., 2006; Lasserre et al., 2009) can all have a profound effect on timber quality. The influence of both early respacing and thinning was confirmed across various species (Cameron, 2002; Cameron et al., 2015; Eriksson et al., 2006; Moore et al., 2009; Pape, 1999; Savill and Sandels, 1983), as was the effect of site (Kimberley et al., 2015; Kimberley et al., 2017; Lasserre et al., 2008; Macdonald, 2002). However, the impact of these factors is neither unidirectional nor unconditional, as the relationships change with interactions and time (Zobel and van Buijtenen, 1989). Stem quality was also reported not to be affected with increasing species diversity. Individual tree and stand properties were found to have a larger impact on stem quality, such as stand structure, tree and crown properties (Benneter et al., 2018).

The current study aims to examine how the shape and social position of the crown together with stem shape influence the mechanical properties of wood, which is still relatively unknown. The main objective was to evaluate the relationships between certain aspects of a tree's phenotype and the grade-determining mechanical properties of the end product (sawn structural-sized timber). The secondary objectives were to examine whether similar relationships can be observed in mechanical properties of small clear specimens of wood without any knots and in acoustic velocity of standing trees. The current study implements a novel approach examining the relationships across multiple levels by evaluating the acoustic velocity of standing trees alongside the mechanical properties of harvested and processed timber.

2. Material and methods

2.1. Stand selection

Three softwood species grown in Ireland were chosen for this study: Douglas-fir, Norway spruce and Sitka spruce. Two pure even-aged stands per species were selected. The selection criteria were as follows: climatic region, planting density, stand age and yield class. One stand of the pair was thinned using a combination of thinning from below and systematic thinning, while the other was not thinned. This was done to expand the range of growing space of the crowns represented in the current study, *i.e.* to include as much variation in crown and stem development as possible. The thinned Sitka spruce stand was thinned four times (most recently in 2011), thinned Norway spruce stand three times (most recently in 2011) and thinned Douglas-fir two times (most recently in 2000). More information about the stands is available in a parallel study (Krajnc et al., 2019), which examined the effect of thinning on mechanical properties. The stands were chosen using the inventory data of Coillte, which manages the state-owned forests in the Republic of Ireland. The chosen pairs of stands were similar in initial planting spacing (2 m × 2 m), age (five planted in 1963, one in 1967), site productivity, climate and yield class. They were located in County Galway (Ireland) on shallow brown earths, underlain by limestone bedrock. The stands were felled for the study in the first half of 2017 and none of the trees were pruned.

2.2. Sampling and material

Within each of the six stands, five sets of random coordinates were generated and randomly assigned to one of the five crown social classes using the Kraft classification system (Assmann, 1970). This process was repeated once. The coordinates were then found in the field and the closest tree matching the assigned social class was identified by two persons observing the same tree from different angles. Other criteria used were that diameter at breast height should exceed 15 cm and that the first six meters of the stem were of sawlog quality. The selected tree together with the nine closest trees formed each plot, giving circular plots of varying diameters with ten trees each (20 plots per 3 species for a total of 600 trees). Diameter at breast height (d), crown social class, species and the location of each tree in the plot were measured on all trees on the plot. In addition, all tree heights (h) were measured as well as the heights of the crown base using the Vertex IV hypsometer (Hagl, Sweden). Crown ratio (l_{crown}/h) was calculated by dividing the live crown length (l_{crown}) by the tree height. Slenderness (h/d) was determined as the ratio of tree height to diameter at breast height. The crown of each tree was recorded using a Densitometer (Geographic Resource Solutions, California, USA), a vertical sighting device with a mirror inside (periscope). The instrument was mounted on a wooden board and positioned under the eight main crown extremities of each crown. At each point, the distance from the instrument to the stem was measured together with a reverse azimuth of each point. Half of the corresponding d was added to those distances to reference them to a common point in the stem, and using the azimuths, the crown data was converted into coordinate pairs. Crown projection areas (cpa) were calculated by applying the shoelace algorithm (also known as Gausss area formula) to crown coordinates for each tree (Pretzsch, 2009). Crown eccentricity (exc) was calculated as the distance between the stem centre and crown centre of gravity divided by diameter at breast height. The crown roundness (r_{min}/r_{max}) was derived from the ratio of minimum crown radius to the maximum one (Pretzsch, 2014).

The stress wave velocity of Douglas-fir, Sitka or Norway spruce tree was determined using the TreeSonic device (Fakopp Bt, Sopron, Hungary) in the longitudinal direction at breast height, perpendicular to prevailing wind direction (SE side). This method was found to be suitable for comparing timber quality on standing trees by several studies (Legg and Bradley, 2016; Ross, 2015; Simic et al., 2018). The longitudinal velocity was not recorded in broadleaf trees (110 of 600 total trees). An additional three trees of Douglas-fir were not measured due to poor accessibility in the field. The longitudinal velocities were measured on a total of 487 trees, of which 145 were Douglas-fir, 213 Norway spruce and 129 Sitka spruce. The broadleaf trees in the studied stands occurred as a result of natural regeneration in combination with increased light availability due to thinning or natural mortality. As those trees were in the bottom layer of the stands (i.e. dominated or suppressed), their influence on the growth of the middle and top layer of the stand were disregarded for the purpose of this study. This was also supported by their heights and diameters at breast height, as they were mostly under 10 m in height and of diameters at breast height of around 10 cm.

The first two 3 meter logs from the plot centre trees (total of 60 trees, 119 logs as one broke in transport) were extracted and cut into structural timber with cross-sectional dimensions of 45 mm (×) 100 mm, producing 1342 pieces of timber. Before cutting the logs, the outer border of the juvenile core of 15 growth rings was marked to assess the proportion of juvenile wood in each board to determine its radial position (three categories: no juvenile wood, < 50%, > 50%). The cut boards were kiln dried and then passed through a GoldenEye 702 X-ray grading machine (Microtec, Brixen, Italy), obtaining an overall machine knottiness value for each board. Before further testing, the boards were transported to the testing laboratory in Galway and stored in a conditioning chamber at 20 °C and 65% relative humidity. After attaining constant mass, all boards were destructively tested in a four-point bending test, as per EN 408 (CEN, 2012). Immediately after testing the moisture content was determined in accordance with EN 13183-1 (CEN, 2002) and all grade-determining parameters were adjusted to a 12% moisture content values as specified in EN 384 (CEN, 2010). From each of the tested boards, a small clear specimen with dimensions 20 mm × 20 mm × 300 mm was cut as close as possible to the fracture location, yielding 1303 small clear samples. Following further conditioning, and upon attaining constant mass, they were tested in three-point bending in accordance with the BS 373 (British Standards Institution, 1957).

2.3. Data analysis

The analysis was carried in an open source statistical environment R (Core Team, 2018) using Bayesian multilevel models (also known as hierarchical or mixed effects models). The Bayesian approach was preferred over a frequentist one, as it warrants a more informative inference by incorporating uncertainty into the model itself (Kruschke, 2014). Modelling was carried out in Stan (Carpenter et al., 2017) with the help of the R package *brms*. The priors used were weakly informative and based on values from previous studies (Table A.1). Using collected data and prior distributions, Stan performs a Markov chain Monte Carlo sampling to converge on the posterior distributions. The three mechanical properties, knottiness and acoustic velocity were modelled (y_{ijk}) and a sensitivity analysis was performed *post hoc* using a best-fit model to test any other interactions between variables. The model to be fitted was formulated as follows:

$$y_{ijk} = a_0 + a_1C_a + a_2C_{ra} + a_3C_e + a_4C_{ro} + a_5C_{sc} + a_6S + a_7P_r + a_8Pl + b_s + b_t + b_i + b_{ij} + b_{ijk}$$

The crown-derived explanatory variables were crown area (C_a), crown ratio C_{ra}, crown eccentricity (C_e), crown roundness (C_{ro}) and crown social class (C_{sc}). Slenderness was also included (S), as were the group-level effects (random effects) of species (b_s), stand thinning regime (b_t, thinned or unthinned) as well as the nested effects of stand (b_i), plot-in-stand (b_{ij}) and tree-in-plot-in-stand (b_{ijk}). Additionally, the radial (P_r) and longitudinal position (P_l, first or second log) of individual boards within a tree were included as an explanatory variable to account for the with-in tree variation of structural-sized boards and small clear samples. The low number of groups in some group-level effects (species, stand thinning regime) was not considered problematic, as multilevel modelling should perform similarly to no-pooling regression in such cases (Gelman and Hill, 2006). The models were inspected for convergence before using the posterior distributions for inference (McElreath, 2016). Bayes factors (BF) were used to quantify the uncertainty of the multilevel models, as using them conveys a relative measure of evidence strength without relying on tests of significance (Gelman et al., 2004; Kruschke, 2014). They were computed as ratios of posterior probability under the hypothesis against the probability of the alternative. Depending on values of the computed Bayes factor,

Table 1
Mean values of tree and crown properties by species (standard deviation in brackets), broadleaf species not included.

Crown social class	N	d	h/d	Crown properties				v
				l_{crown}/h	cpa	exc	r_{min}/r_{max}	
Douglas-fir								
Predominant	21	40 (5)	61 (5)	44 (8)	18 (8)	1.6 (1)	41 (14)	3820 (327)
Dominant	18	35 (7)	66 (6)	39 (8)	15 (6)	2.3 (1.7)	46 (14)	3927 (352)
Co-dominant	51	25 (6)	80 (11)	33 (8)	8 (5)	2.1 (3.5)	41 (14)	3948 (356)
Dominated	21	20 (5)	89 (14)	30 (9)	6 (4)	2.6 (1.5)	35 (18)	4047 (425)
Overtopped	37	17 (5)	94 (19)	28 (9)	6 (5)	3.4 (2)	26 (13)	4113 (352)
Norway spruce								
Predominant	11	42 (9)	62 (8)	41 (9)	13 (6)	0.7 (0.4)	55 (16)	3778 (313)
Dominant	36	36 (9)	71 (10)	38 (9)	8 (6)	0.9 (0.6)	48 (13)	3788 (338)
Co-dominant	79	33 (9)	76 (13)	36 (9)	7 (6)	1.2 (0.6)	39 (16)	4002 (289)
Dominated	17	23 (7)	91 (15)	33 (13)	4 (4)	1.7 (0.7)	33 (13)	4120 (216)
Overtopped	34	16 (5)	96 (18)	25 (11)	4 (5)	2.4 (1.9)	34 (16)	4107 (276)
Sitka spruce								
Predominant	16	54 (8)	58 (10)	50 (9)	23 (13)	1.6 (1.2)	41 (15)	3707 (264)
Dominant	31	47 (6)	66 (7)	44 (5)	20 (10)	1.3 (0.7)	42 (13)	3876 (403)
Co-dominant	66	39 (6)	74 (10)	37 (7)	10 (6)	1.6 (0.9)	36 (15)	3946 (309)
Dominated	24	30 (6)	80 (11)	28 (6)	6 (5)	1.7 (1.2)	34 (14)	4152 (467)
Overtopped	28	25 (7)	82 (18)	30 (14)	7 (7)	2.3 (1.6)	28 (18)	3880 (322)

Note: d – diameter at breast height in cm, h/d – slenderness, l_{crown}/h – ratio of crown length to tree height in per cent, cpa – crown projection area in m^2, exc – crown eccentricity, r_{min}/r_{max} – crown roundness in per cent, v – acoustic velocity in m/s.

evidence for the first hypothesis was considered anecdotal ($1 < BF < 2$), moderate ($2 < BF < 4$) or strong ($BF > 4$). The inverse of those values were used on describing the evidence favouring the alternative hypothesis ($BF < 0$).

3. Results

3.1. Tree-level analysis

The distribution of the trees included in this study by crown social classes and predominant species can be seen in Table 1. As expected, diameter at breast height decreases with the declining dominance, as do crown ratio and crown projection area. Suppressed trees appear to have more eccentric crowns, which are also less round compared to trees from the upper layer. The size of the differences appears to be species dependant.

The median longitudinal velocity appears to increase with the declining social status of trees (Table 1). While the absolute values of the velocity differ between the species, the trend across the social classes is the same across the three studied species.

The relationship between the longitudinal velocity and stem or crown characteristics was examined in more detail using a multilevel model, with longitudinal velocity being the dependant variable. The effect of crown social class can be seen in Fig. 1. Compared to co-dominant trees, dominated trees have higher longitudinal velocities, followed by overtopped trees. Pre-dominant and dominant trees have slightly lower speeds, the differences to co-dominant trees are not as distinct. A decline in social class of trees is related with higher longitudinal velocities than co-dominant trees, while an increase in dominance leads to lower velocities, indicating a negative change in stiffness.

To better quantify the uncertainty of the model, Bayes factors were calculated using a hypothesis of a negative relationship between crown properties and longitudinal velocity. The results can be seen in Table 2.

There is strong evidence in favour of dominant and predominant trees having lower longitudinal velocities compared to co-dominant trees of each species. When comparing dominated trees to the latter, the opposite can be found. The likelihood of the relationships illustrated in Fig. 1 varies with species, however, the trends are similar among the species. The effect of crown area and slenderness is dependant on the social class of the tree. Slenderness is positively connected with the longitudinal velocity in co-dominant, dominant and predominant trees while reducing velocity in dominated and overtopped trees. Crown area is positively connected with the longitudinal velocity in predominant trees and negatively in dominated trees. In all other social classes no conclusive evidence was found with regard to the effect of crown area on longitudinal velocity. Crown eccentricity increases the longitudinal velocity (Bayes factor of 0.1), while there is no evidence that crown ratio and roundness (Bayes factors of 0.9 and 0.7, respectively) influence the longitudinal velocity.

3.2. Timber-level analysis

Table 3 shows the mean values of the mechanical properties for each species and crown social class on both specimen sizes. Standard deviations are given in Table A.2. Aside from the differences between species, no clear trends are identifiable among timber from different social classes. This is expected due to a relatively high variation with-in tree, which can mask differences between social classes. In order to examine the relationships between timber quality (as measured by the elastic modulus, bending strength, density and knottiness) and tree or crown characteristics, each of the properties was examined using a multilevel model with the same explanatory variables as before.

This was done on two separate datasets, structural sized timber and small clear specimens. In the latter there is no direct effect of knots on the studied mechanical properties, as there were no knots in small clear samples. The knottiness parameter, as measured by the GoldenEye-702 was also modelled to examine how crown development influences the knot content of boards. Model summaries can found in Table A.3. The effect of crown social class on the modelled properties across the two specimen sizes can be seen in Figs. 2 and 3, which show the mean posterior values of the effect of crown class for each species. Only density from structural-sized timber is displayed in Fig. 3, as densities of both specimen sizes were determined on defect-free samples coming from the same radial and longitudinal position.

The trends of the elastic modulus and bending strength in both specimen sizes and the three studied species appear to be the same, approximately following the shape of an asymmetrical letter W. The timber from overtopped trees has the highest elastic modulus and bending strength relative to other crown social classes, which is

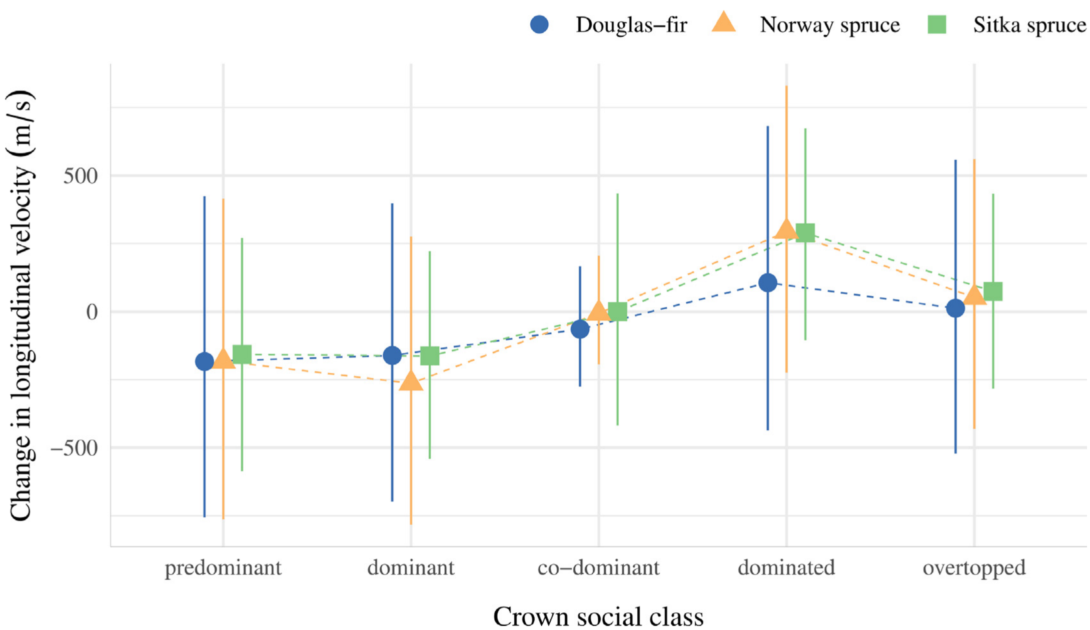

Fig. 1. The effect of crown social class on longitudinal velocity of trees relative to co-dominant trees of Sitka spruce, showing posterior distribution of values (points showing median, lines representing a probability mass of 95%).

especially evident in Norway spruce. There is a noticeable drop in both characteristics in dominant and dominated trees when compared to co-dominant trees, while predominant trees seem less affected.

With regard to density, the trends across the crown social classes seem more species dependant. Overtopped trees have absolutely the highest clear-wood density. With the exception of Douglas-fir, the trend still follows a shape of an asymmetrical letter W. Comparing the differences between social classes relative to the mean values of the mechanical properties, the differences in density between social classes are less evident than differences in the elastic modulus or bending strength, but are still present. It is worth pointing out that the effect of knots seems the most dependant on species out of the studied properties (Fig. 3). In line with previous expectations, more dominant trees a greater proportion of knots. The differences between dominant, co-dominant and dominated trees appear smaller. To examine the likelihood of the trends shown in Figs. 2 and 3, Bayes factors were calculated as ratios of probability of each crown or tree property negatively affecting the examined wood properties to its alternative. The calculated values can be seen in Tables 4,5.

Relative to the co-dominant trees of each species, timber from dominated trees will very likely have lower mechanical properties (Table 4), as confirmed in almost all (6/6 in Douglas-fir, 5/6 in Norway spruce and 5/6 in Sitka spruce) examined mechanical properties in both structural-sized timber and small clear specimens. It is also more likely that timber from overtopped trees will have higher mechanical properties. With regard to the effect of other social classes, it can be concluded that while the evidence is inconclusive, dominant trees are more likely to have lower mechanical properties while timber from predominant trees will more likely have higher mechanical properties when compared to co-dominant trees. The strength of the effect of social classes on timber quality is the least evident in Sitka spruce.

The knottiness of the sawn timber in the current study is positively correlated with slenderness in co-dominant trees and negatively in overtopped trees. All other crown variables seem to impact the knottiness positively, although the evidence of these relationships is inconclusive: increasing crown ratio, roundness, eccentricity or projection area leads to an increase in the amount and size of knots in sawn timber. Comparing the overall size and the amount of knots among timber from different social classes, dominated trees have higher knottiness than co-dominant trees in Douglas-fir and Norway spruce. Opposite trends can be seen in other social classes, however, with inconclusive evidence.

The current study found no evidence that crown ratio, eccentricity or roundness affect the examined wood properties in either structural-

Table 2
Bayes factors of the effect of crown classes on longitudinal velocity relative to the co-dominant class of each species and of the effect of crown area and tree slenderness across the crown social classes.

	Crown social class				
	Predominant	Dominant	Co-dominant	Dominated	Overtopped
Species					
Douglas-fir	1.4	1.3	*	0.2	0.3
Norway spruce	**3.1**	**8.1**	*	0.1	0.6
Sitka spruce	**3.2**	**4**	*	0.1	0.5
Other					
Crown area	**3.4**	1.3	0.6	0.1	0.9
Stem slenderness	0.3	0.3	0	**11.6**	**5.3**

Note: moderate evidence of lower properties/negative influence in bold (Bayes factor of 2 or more), moderate evidence of higher properties/positive influence underlined (Bayes factor of 0.5 or less). The effect of crown social class relative to co-dominant trees *, the effect of crown area and tree slenderness as positive or negative across social classes.

Table 3
Sawn timber and small clear samples properties by species and crown social class – mean values.

	Structural sized timber					Small clear specimens			
	N	$E_{m,0}$	f_m	ρ	knot.	N	$E_{m,0}$	f_m	ρ
Douglas-fir									
Predominant	92	12174	57	554	3996	91	11184	100	562
Dominant	72	12252	53	575	3897	71	11110	99	574
Co-dominant	57	12959	63	583	3669	56	11207	103	581
Dominated	29	12702	56	540	3795	29	10422	95	540
Overtopped	21	11560	53	528	4134	21	9560	88	533
Norway spruce									
Predominant	133	9632	43	438	3228	133	8342	69	442
Dominant	93	9153	43	436	4664	92	8185	67	435
Co-dominant	69	9700	45	439	4296	69	8184	71	448
Dominated	43	8871	42	412	4806	43	7687	68	422
Overtopped	30	10251	45	451	4800	30	8740	78	467
Sitka spruce									
Predominant	233	9455	46	428	3621	224	7705	65	427
Dominant	195	10525	50	449	3365	185	8546	70	451
Co-dominant	131	10338	52	442	3281	118	8342	69	449
Dominated	77	9992	49	451	4487	76	8770	73	460
Overtopped	67	8622	45	406	4389	65	7304	65	409

Note: elastic modulus and bending strength in MPa, density in kg m^{-3}, knottiness unitless.

sized timber or in small clear specimens (Table 5). The effect of crown projection area varies between the studied crown classes, but is more often of a positive nature. The positive effect is especially evident in dominant and dominated trees and was confirmed in multiple wood properties. In co-dominant trees, wood density is very likely negatively affected as the crown area increases. The evidence also shows that the effect of slenderness on the studied mechanical properties is dependant on the social class of the tree. In overtopped trees increasing slenderness leads to lowering of the mechanical properties. There is also strong indication that increasing slenderness leads to a corresponding increase in the elastic modulus, bending strength and density of timber in co-dominant trees. The effect of slenderness varies in other social classes, it is positive with increasing dominance and negative in suppressed trees.

4. Discussion

Various crown and tree characteristics can have a considerable effect on both acoustic velocity of individual trees and on mechanical properties of the sawn timber and small clear specimens, as found by the current study. There are substantial differences in acoustic velocity and mechanical properties between different crown social classes. Higher acoustic velocities were found in co-dominant trees than dominant trees, which was also confirmed in a study done on radiata pine (Merlo et al., 2013). Suppressed trees have the highest acoustic velocities across the social classes. Comparing the studied mechanical properties across social classes, the findings of the current study are in line with previous studies. Higher wood densities of suppressed trees were reported by multiple studies across several species (Amarasekara and Denne, 2002; Deng et al., 2014; Johansson, 1993). As there is a relatively high degree of association between density, elastic modulus and bending strength in timber, similar trends across social classes were expected and identified in both structural-sized boards and small clear specimens.

Tree slenderness affects both tree stiffness and the properties of sawn timber to a varying extent depending on the crown social class. Both direction and the size of the effect vary. It is negative in suppressed trees (increasing slenderness leads to a decrease in velocity or mechanical properties) and positive in dominant and co-dominant trees. While several past studies have shown that slenderness can be used to predict the timber stiffness (Lasserre et al., 2009; Roth et al., 2007; Searles, 2012) or timber strength (Lindström et al., 2009; Pretzsch and Rais, 2016), the findings of the current study suggest that these relationships are likely to be dependant on social classes, as correctly suggested by Pretzsch and Rais (2016). The results of the current study also indicate that the difference in timber quality between social classes may not be explained by branchiness alone, as differences were confirmed in both structural-sized timber and small clear samples without any knots.

Similarly, the effect of crown projection area on tree acoustic velocity and/or timber mechanical properties differs between social classes. In general, it is positive, so an increase in crown projection area leads to an increase in acoustic velocity and/or timber mechanical properties. The effect is more evident in wood properties than on an individual tree level. Other crown properties, such as crown eccentricity, ratio or roundness appear to have a negligible effect on mechanical properties or acoustic velocity. Although timber quality models designed in the past frequently treat crown shape as a predictor of overall timber quality (Houllier et al., 1995; Mäkelä et al., 2011), the current study suggests that more detailed research is needed on the relationships between tree crown, stem and timber properties. By providing a better understanding of the associations between them, silviculture could be used to improve the overall quality of the timber produced.

Past studies of the relationships between crowns and wood properties (Amarasekara and Denne, 2002; Deng et al., 2014; Merlo et al., 2013) have normally used a narrower classification system with three social classes, whereas the current study classified trees' crowns into five social classes. If the results of the current study are grouped from five classes into three, the results are in line with previous findings. As such it was confirmed that timber from suppressed trees has higher wood density, elastic modulus and bending strength with dominance also having an effect. Results indicate that division of trees into five crown social classes is sensible, due to the differences found in mechanical properties among the classes. For example, dominated and overtopped trees affect the timber to different degrees, even though they would both be grouped into a *suppressed* category. Similarly predominant and dominant trees would also be grouped into one category *dominant*. In both cases the direction of the effect is the same for both social classes when grouped into one grouped category.

The likelihood of the effect of various crown properties on timber properties varies among the three studied species. While the relationships are similar among the three species, they are more distinct in Douglas-fir and Norway spruce than in Sitka spruce. This could be related to differences in growth rate or in shade tolerance of individual species, as proposed by Chen et al. (2017), who found similar differences in subtropical species. The differences could also be a consequence of species distinctions on a cellular level (different latewood-earlywood proportions, microfibril angle, …). The distinctions between species indicate that the effect of species should not be disregarded when studying the relationships between crowns, stems and timber quality. Further research is needed to provide possible explanations for those differences, including a wider range of species.

The results of the current study confirm that there is a relationship between crown and wood properties, both in structural-sized timber and small clear specimens. A combination of causal mechanisms as suggested by Larson (1969), acting in harmony, could explain the differences in wood properties by crown size and crown social status identified in the current study. The main cause of differences is most likely a combination of two factors, differences in light availability and in the mechanical loading of the crowns. The former will affect the growth and development of the crown as a whole, directly affecting the production of growth regulators and the amount of photosynthates. The varying shapes and centres of gravities of crowns will lead to different mechanical stresses to different parts of the stem, likely increasing the variation in mechanical properties of the stem. The current study found

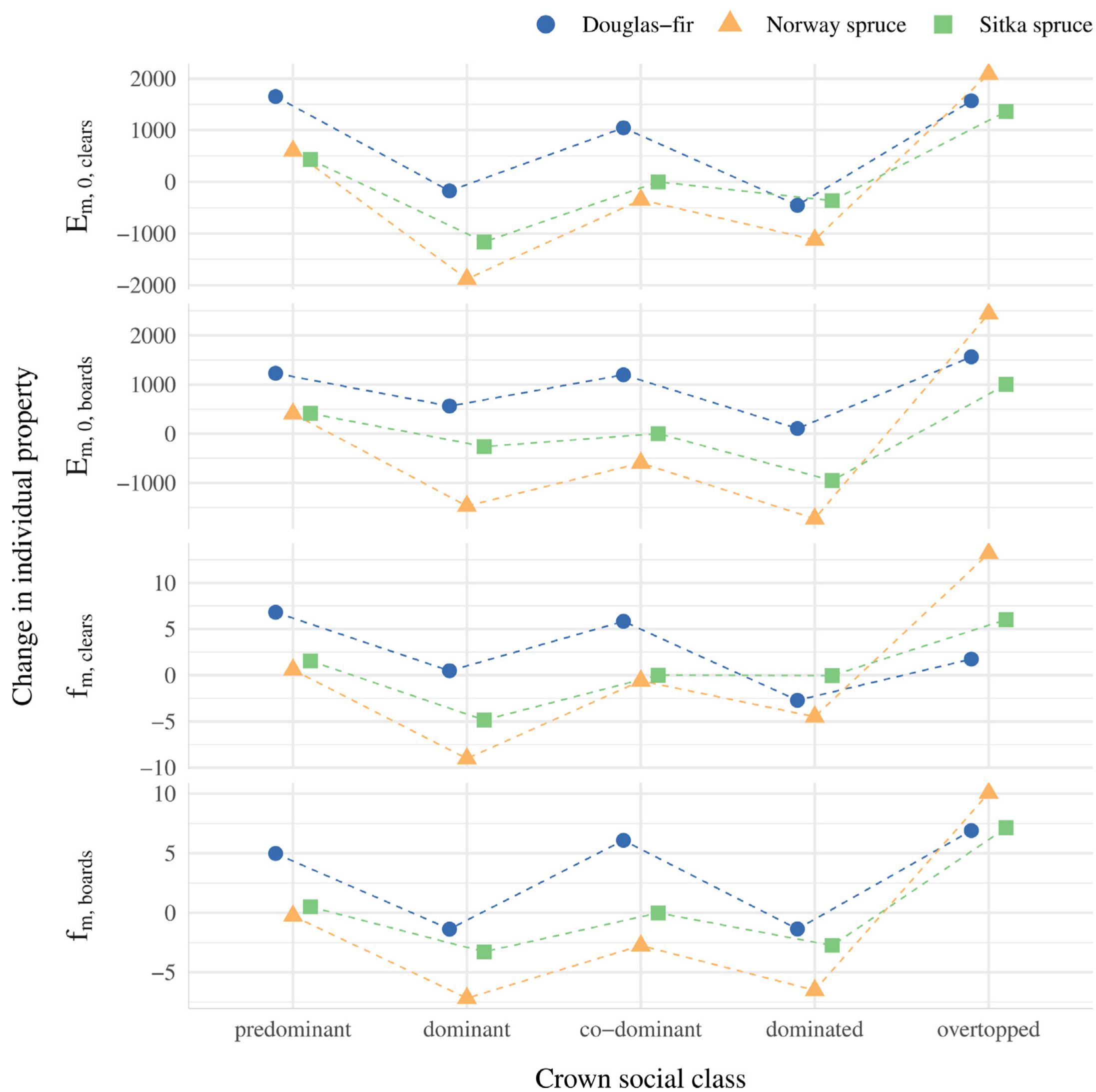

Fig. 2. The effect of crown social class on elastic modulus and bending strength relative to co-dominant trees of Sitka spruce, showing medians of posterior distributions only for clarity. Elastic modulus and bending strength in MPa.

that more suppressed trees have smaller, more eccentric crowns, which are also less round than those of more dominant trees. While an increase in variation with increasing suppression can be seen in some of the mechanical properties of the species considered in this study, the effect is not uniform across species or mechanical properties. More research is needed to provide a better understanding of the interactions between causal mechanisms and relationships between crown and wood properties.

5. Conclusions

Several conclusions can be made with regard to silvicultural practice in pure even-aged stands, based on the results of the current study. As grading of structural timber into strength classes is normally based on the three grade-determining properties on a population level, a small shift in one characteristic value of the grade-limiting property can potentially have a substantial effect on the end grade of the timber from an individual stand. Considering the quality of the end product (*i.e.* structural-sized timber), little is gained by removing suppressed trees early or by even removing them at all, assuming they show potential for saw log quality. If their competition is holding back growth of trees with better potential, they should be removed to facilitate yield transfer to more promising trees. On the contrary, the opposite statements apply to predominant and dominant trees, although the magnitude of their effect is smaller than when looking at suppressed trees. With this in mind, the results of the current study indicate, that in order to maximize the quality of the timber produced on a stand level, predominant and dominant trees are less desirable in the final stand composition, and should be removed during thinning, when feasible. Co-dominant trees, on the other hand, should be kept, as they produce timber of relatively high quality. These findings indicate that both thinning from below or thinning from above can be detrimental to the overall quality of the timber produced. Combining different thinning systems appears to be the best approach to increasing timber quality when thinning.

The results of the current study suggest that silvicultural systems, which increase the variability of the vertical stand structure in the upper stand layer are less favourable when considering the quality of softwoods timber produced on a stand level. Thinning systems which favour the removal of high dominance trees and do not remove suppressed trees should be taken into consideration, when optimizing the quality of the timber produced. Such systems may also be combined with high-density regeneration (natural or artificial), as increased levels of competition in the early years of a stand also increase slenderness and decrease the juvenile core. Both can lead to an increase in overall mechanical properties of timber. Other factors should be considered alongside these recommendations, as leaving suppressed trees where

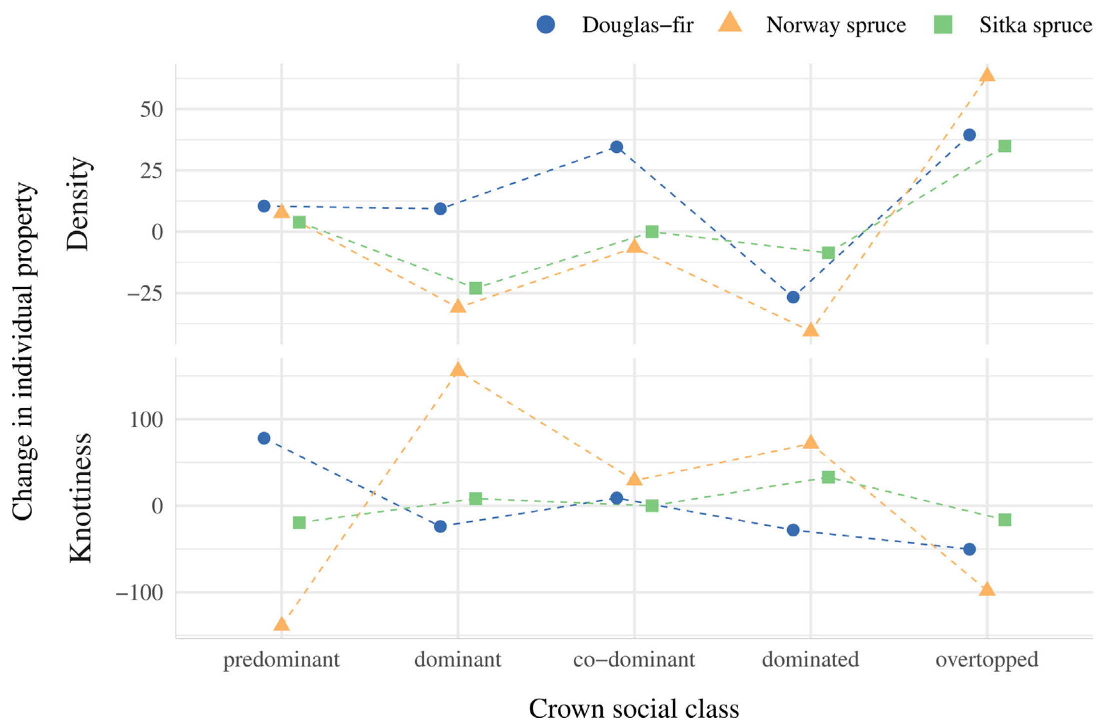

Fig. 3. The effect of crown social class on clear-wood density and structural-sized board knottiness, showing only medians of posterior distributions for clarity. Density in kg m^{-3}, knottiness unitless.

Table 4
Evidence strength of the effect of crown classes quantified with Bayes factors, relative to co-dominant crown social class of each species.

	Structural sized timber				Small clear specimens		
	$E_{m,0}$	f_m	ρ	knot.	$E_{m,0}$	f_m	ρ
Douglas-fir							
Predominant	**2.2**	1.1	0.8	1	0.6	1.2	0.9
Dominant	**2.3**	1.8	1.1	1.5	**2.7**	**3.1**	**2.2**
Co-dominant	*	*	*	*	*	*	*
Dominated	**6.6**	**4.1**	1.1	**2**	**3.6**	**2.9**	**3.4**
Overtopped	0.9	0.8	1.2	0.8	0.7	0.9	1.7
Norway spruce							
Predominant	0.7	0.7	1.9	0.5	0.4	0.7	0.8
Dominant	**2.1**	**2.8**	0.6	1.8	**3.6**	**2**	**3.1**
Co-dominant	*	*	*	*	*	*	*
dominated	**2.9**	**2.7**	0.9	**2.3**	**2**	1.7	1.8
Overtopped	0.1	0.2	1.7	0.1	0.1	0.2	0.1
Sitka spruce							
Predominant	0.9	0.7	1.1	0.7	0.7	0.9	0.8
Dominant	**2.2**	**2.3**	0.9	1.2	**2.9**	1.7	**2.2**
Co-dominant	*	*	*	*	*	*	*
Dominated	1.4	1.1	0.8	1.9	1.4	1.6	1
Overtopped	0.3	0.4	1.1	0.5	0.3	0.3	0.4

Note: moderate evidence of lower properties relative to co-dominant trees in bold (Bayes factor greater or equal to 2), moderate evidence of higher properties underlined (Bayes factor of 0.33 or less).
Reference level co-dominant class of each species.

possible has other advantages as well. Non-removal of suppressed trees is cost-effective and improves the overall strength grade of the timber harvested. They also provide a natural backup in case of a catastrophic event affecting upper and middle stand layers. However, it is worth noting that adjusting the proportions of social classes in favour to suppressed trees can result in more stand damage due to wind. The findings indicate that it is possible to influence timber quality in the forests by removing trees of defined characteristics and with retaining

Table 5
Evidence strength of the effect of crown and tree properties quantified with Bayes factors.

	Structural sized timber				Small clear specimens		
	$E_{m,0}$	f_m	ρ	knot.	$E_{m,0}$	f_m	ρ
Crown projection area							
Predominant	0.5	0.8	0.1	1.9	1	**7.3**	1
Dominant	0.1	0.1	0.2	0.3	0.1	1.6	0.1
Co-dominant	**4.9**	**5.2**	**9**	1.6	**4.9**	0.3	**5.7**
Dominated	0.1	0.1	3.2	0.2	0	1	0.1
Overtopped	0.5	0.6	1.3	0.5	0.6	1.7	0.5
Slenderness							
Predominant	1	1.1	**4.6**	1	1	0.4	0.8
Dominant	1.5	1.7	3	1.2	0.5	0.6	1.7
Co-dominant	0	0	**7.3**	0	0	0	0
Dominated	2.3	3.2	0.3	1.6	3.2	1	**5.2**
Overtopped	**19**	**13.3**	0.4	**9**	**15.7**	**6.1**	**9**
Crown							
Ratio	1.1	0.7	1.5	0.5	1.1	0.5	0.5
Roundness	**4.6**	1.9	0.7	0.6	1.6	0.8	1.6
Eccentricity	0.8	0.6	0.9	0.4	1.5	0.5	1.6

Note: strong evidence of negative influence in bold (Bayes factor greater or equal to 4), strong evidence of positive influence underlined (Bayes factor of 0.2 or less).

the best of co-dominant and suppressed trees to increase the overall timber quality on a stand level. As the quality of the timber produced is only one aspect of forest management, the findings of the current study do not represent a prescription for growing higher quality timber. Instead they represent the summary of what should be taken into account when aiming to improve the quality of the timber produced by adjusting proportions of social classes with thinning.

The current study shows that further improvement of silviculture is still possible, especially when considering optimization of forest management for quality. More targeted research into the effect of silvicultural systems on timber quality in conjunction with stand social composition is needed, focused on different climates, sites and species. New technology, such as terrestrial laser scanning could provide a valuable addition in evaluating the current state of competition, including rapid assessment of crown social positions. Future studies of how to manipulate mechanical properties of timber with silvicultural are therefore recommended in order to better elucidate the relationship between quantity and quality of the timber produced.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.foreco.2018.12.043.

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