Annals of Forest Science (2019) 76:3
https://doi.org/10.1007/s13595-018-0787-6

RESEARCH PAPER

The effect of thinning on mechanical properties of Douglas fir, Norway spruce, and Sitka spruce

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Received: 15 August 2018 / Accepted: 3 December 2018

Abstract

• ***Key message*** **Thinning affects negatively the quality of sawn timber of Douglas fir, Norway spruce, and Sitka spruce. The effect was confirmed in structural-sized boards and small clear samples, and on standing trees using longitudinal velocity. The loss of quality across the three species due to thinning rarely exceeds 20% and is in most cases smaller than 5%.**

• ***Context*** The relationship between silvicultural management and the quality of timber produced is not entirely elucidated.

• ***Aims*** The effects of thinning on structural grade-determining properties of wood (elastic modulus, bending strength and density) were studied on Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Norway spruce (*Picea abies* (L.) H. Karst), and Sitka spruce (*Picea sitchensis* (Bong.) Carr)).

• ***Methods*** Acoustic velocity was measured in a total of 487 trees and their crown social status was recorded. Sixty trees were selected and cut into structural-sized boards ($N = 1343$). The amount of knots in each board was quantified using the grading machine GoldenEye702. All boards were destructively tested in four-point bending, after which a small clear specimen was cut from each board and again tested in bending ($N = 1303$). Specific stiffness and specific strength were used to estimate the size of the effect accounting for differing influence of thinning across the before-mentioned properties.

• ***Results*** Thinning reduces all three properties with the likelihood and magnitude of the effect varying between species. The loss of quality due to thinning rarely exceeds 20% and is in most cases smaller than 5%. The effect of thinning and its size were also confirmed on the full sample of trees by using longitudinal velocity.

• ***Conclusion*** The results give a clearer idea of what the trade-offs are between timber quality and silvicultural management.

Keywords Thinning · Wood quality · Softwoods · Bayesian analysis

1 Introduction

Silvicultural practice can be defined as the sum of all human interventions during the life of a forest, from initial forming of the stand to the felling of individuals or groups of trees. While several authors have looked at individual species and how thinning affects individual wood properties, there is a shortage of comprehensive studies examining the effect of thinning on overall timber quality, as defined through the strength grade-determining parameters used in the European strength classification system for structural timber EN 338 (CEN 2016)—namely modulus of elasticity (MOE), bending strength (previously known as modulus of rupture, MOR), and density of clear wood.

The effect of thinning on the grade-determining properties of softwoods is in general negative. In Norway spruce, thinning was shown to decrease wood density (Pape 1999a; Jaakkola et al. 2005a, 2006; Grammel 1990; Herman et al. 1998), while similar trends were also found in Douglas fir (Hapla 1985), radiata pine (Bues 1985; Cown 1973; Cown and McConchie 1982; Kimberley et al. 2015), loblolly pine (Aslezaeim 2016), Sitka spruce (Evertsen and O'Brien 1985; Macdonald 2002), and Scots pine (Peltola et al. 2007). Most

Handling Editor: Jean-Michel Leban

Contributions of the co-authors Conceptualization: All; Methodology: All; Validation: All; Formal Analysis: LK; Investigation: LK; Writing – original draft:.LK.; Writing – review & editing: AH, NF; Supervision: AH, NF; Funding acquisition: AH, NF kindly provided by the Murray Timber Group while Martin Bacher from MiCROTEC helped with the scanning of the boards.

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Published online: 07 January 2019

authors seem to agree that those changes are a consequence of wider tree rings from accelerated growth after the thinning. A small number of studies reported no change in density after early respacing or thinning—in Sitka spruce (Moore et al. 2009), Douglas fir (Kimberley et al. 2017), or black spruce (*Picea mariana* (Mill.) BSP) (Vincent et al. 2011). Wood density of Norway spruce was also reported to be affected by whether the trees come from even-aged or uneven-aged stands (Piispanen et al. 2014), while variation of density is bigger within annual rings than along tree height (Jyske et al. 2008). A recent study by Zeller et al. (2017) also found that trees from a mixed-species stand have a lower wood density than trees from monocultures of Scots pine and European beech.

A significantly lower number of studies have dealt with the impact of thinning on MOE or MOR. Moore et al. (2009) found that early respacing significantly reduced MOE and MOR in Sitka spruce, while a slight increase in MOE was reported in black spruce for thinned stands with no increase in MOE variation (Vincent et al. 2011). No changes in MOE or MOR were reported with varying silvicultural intensity in young Loblolly pine (Aslezaeim 2016). The extent of how MOE is affected by silvicultural intensity seems to be at least partly governed by genetics, as seen in young loblolly pine (Roth et al. 2007). The impact of thinning is also dependent on final stand density (Moore et al. 2015). MOE and bending strength were found to be positively related with crown length in black spruce (Liu et al. 2007), and also affected by the stand structure (Torquato et al. 2014). No decrease in MOE of Douglas fir trees was found due to thinning by Lowell et al. (2014).

Other indirect evidence is available on how thinning affects timber quality. For example, thinning affects crowns in a variety of ways (see Pretzsch and Rais 2016). Amarasekara and Denne (2002) studied the implications of crown size on a variety of wood characteristics. Although suppressed trees had higher wood density than co-dominant or dominant trees, the difference was not statistically significant. Bending strength was shown to decrease with dominance (statistically significant), as did modulus of elasticity (not statistically significant). An analogous study carried out in Southern China on *Pinus massoniana* also confirmed that suppressed trees have higher wood density (Deng et al. 2014). This was also confirmed in Norway spruce (Johansson 1993). Another study from China (Chen et al. 2017) compared suppressed trees to dominant trees of seven subtropical species, and the former were found to have a higher wood density in shade-tolerant species; the opposite was true for shade-intolerant species. Connections between crown development and wood density were also discovered in multiple studies (Lindström 1996; Simpson and Denne 1997). Pretzsch and Rais (2016) also found that in the majority of thinning trials conducted in pure stands, a reduction in stand density led to a decrease in slenderness (tree height/diameter at breast height ratio), while crown ratio (crown length/tree height ratio) and number of primary living branches both increased with declining stand density. Several studies found that tree-to-tree competition releases are associated with an increase in both mean and maximum branch length as well as branch diameter. All of the relevant studies reviewed by Pretzsch and Rais (2016) showed that thinning is also related with lower stem form factors (the ratio of stem volume to the volume of a cylinder of a reference diameter).

With regard to the effects of other silvicultural interventions, several aspects are already well documented (Zobel and van Buijtenen 1989). For example, genetics (Dungey et al. 2006; Roth et al. 2007; Lasserre et al. 2009), fertilizers (Jaakkola et al. 2006), initial spacing (Rais et al. 2014; Aslezaeim 2016; Johansson 1993; Lasserre et al. 2005; Simic et al. 2017), pruning (Makinen et al. 2014), and respacing and thinning all affect wood properties to a varying degree (Brazier 1977; Macdonald 2002; Cameron 2002; Eriksson et al. 2006; Savill and Sandels 1983; Cameron et al. 2015; Pape 1999b). The size of the effect varies between the species and throughout the lifetime of an individual tree.

Various other factors can also impact the properties of wood in trees, including site, soil, or climate (Zobel and van Buijtenen 1989). A review paper focused on Sitka spruce by Macdonald (2002) found that wood density decreases with increasing site productivity; this was recently confirmed in radiata pine (Kimberley et al. 2015) and Douglas fir (Kimberley et al. 2017) as well. The effect of site on dynamic MOE in young radiata pine was also found to be substantial (Watt et al. 2006; Lasserre et al. 2008). Interaction of site and silviculture was also shown to affect both wood density and stress-wave velocity in mid-rotation radiata pine (Carson et al. 2014). Similar results were confirmed in Norway spruce in static bending tests on timber from mature trees (Høibø et al. 2014). Liu et al. (2007) found the opposite in structural-sized timber of black spruce but credited the non-significance to a relatively narrow range of site quality of the studied sites. In a recent study of *Picea glauca*, the stiffness of individual trees as assessed using acoustic velocity was found to increase with tree diameter at breast height and decrease with growth rate, site productivity, and competition pressure (Bérubé-Deschênes et al. 2016).

The current study was designed to address some of the lack of knowledge with regard to the effects of thinning on the grade-determining properties of sawn timber at the end of the rotation period of the forest. The primary objective of the study was to quantify the effect of thinning on the mechanical properties of structural-sized boards and small clear specimens. The secondary objective was to examine whether the identified trends can also be found using acoustic velocities of standing trees on a larger sample. The results of the different approaches were compared, and their differences evaluated. The study also accounts for the potential differences arising from different proportions of crown social classes as a consequence of thinning/non-thinning and was replicated across multiple softwood species.

2 Material and methods

The work was carried out in two parts. In the first part, acoustic velocity was measured on a substantial number of standing trees, spanning across multiple crown social classes, species, and thinning history. In the second part, approximately 10% of sample trees out of the original sample were felled, sawn into structural-sized boards, and the full sample was tested destructively. After the bending tests, a small clear specimen was extracted from each board and its mechanical properties were evaluated. This approach enabled the effect of knots to be quantified, as the small clear samples by definition contain no knots. The discovered trends were then compared to those found from the standing tree measurements to see whether the relationships were the same using the three different measurement methods. The impacts of site, genetics, climate, or planting density on any of the properties were accounted for in the experimental design where applicable.

2.1 Experimental sites

Suitable stands for the study were identified using inventory data from Coillte, the company managing the state-owned forest lands in the Republic of Ireland. Potential sites were screened for stand age, number of thinnings carried out, initial planting density, years of fellings, site productivity (yield class), and dominant species. All of the stands considered were mature species-pure stands located in western Ireland to exclude the effects of climate on the results. The accuracy of the preliminary data and the current state of the stands were assessed with an in situ inventory. Three softwood species were considered in this study, Sitka spruce (*Picea sitchensis* (Bong.) Carr), Norway spruce (*Picea abies* (L.) H. Karst), and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco). Two suitable stands per species were selected with one being thinned at least twice in the last 50 years and the other being an unthinned stand. All chosen stands were located on shallow brown earths (cambisols) underlaid by limestone with frequent outcropping rock, within a 30-km radius of Galway city.

According to the records, the thinned Sitka spruce stand was thinned four times, in 1982, 2001, 2005, and 2011, and the thinned stand of Norway spruce was thinned three times, in 1990, 2005, and 2011. The thinned stand of Douglas fir was thinned less frequently—first in 1986 and then once at the turn of the century. The thinning approach in these stands was a combination of thinning from below and a systematic thinning of trees in rows. None of the trees were pruned. The initial planting spacing was 2 m × 2 m. The stands were planted in 1963 with the exception of the unthinned Norway spruce stand in 1967. All stands were felled for the study in the first half of 2017. More stand level information can be found in Table 1.

2.2 Tree-level measurements

Prior to the field visit, a set of random coordinates was generated within each study stand to choose the sample of trees for each crown social class as first proposed by Kraft in 1888: predominant, dominant, co-dominant, dominated, and overtopped trees (Assmann 1970). The procedure was replicated once for each social class giving a total of 10 sets per stand. In the field, a handheld GPS device was used to find each set of coordinates for each individual tree. The closest tree to those coordinates matching the species and the assigned crown social class was marked to be the center of the plot, with the provision that the first six meters of the tree were of minimum sawlog quality. An experimental plot was established around each selected center tree. The nine closest living trees to the center tree with diameter at breast height over seven centimeters were marked using plastic tags, and a plot was formed around them. The plots were circular with a varying radius, the radius being determined by the distance to the ninth tree (the tree farthest away from the centre tree). This gave a total of 10 sample trees per plot and 100 sample trees per stand. The following parameters were recorded for the sample trees: diameter at breast height, crown social class, species, and coordinates of the tree in the plot. The presence

Table 1 Stand-level characteristics of the six selected stands

Dominant species	Thinning regime	Yield class (m^3 ha^{-1} $year^{-1}$)	Stand density (trees/ha)	Basal area (m^2 ha^{-1})	Median diameter at breast height (cm)	Mean ring width (mm)
Douglas fir	Unthinned	8	1491	59.9	20.6	2.53
	Thinned	10	1124	55.4	29.4	3.41
Norway spruce	Unthinned	18	1552	70.1	23.4	3.95
	Thinned	20	593	54.7	40.0	5.16
Sitka spruce	Unthinned	22	928	89.7	33.6	4.96
	Thinned	22	487	54.0	41.2	5.29

of stumps, standing dead, and fallen dead trees was also recorded to check whether the recorded history of each stand matched with the actual state.

Stress wave velocity was measured using the TreeSonic device (Fakopp Bt, Sopron, Hungary) in the longitudinal direction on the SE side of the sample trees (perpendicular to prevailing wind direction) at the breast height. Sitka spruce, Norway spruce, and Douglas fir totalled to 487 trees measured. Of the 600 trees in the experimental plots, 110 were broadleaved trees from the lower stand layer, and their longitudinal velocity was not measured. The sample trees were then felled and a 6.6-m long first length log was extracted from each of the plot center trees. The logs were delivered to a sawmill and crosscut into two 3-m long logs, with the exception of one log which was broken during extraction. Two 10-cm thick disks per tree were extracted, one from the bottom and another from the top of the long log. Each log/disk combination was numbered, and the outer border of the juvenile core of 15 growth rings was marked and colored white on the bottom face of each log. The white-colored area was later used to assess the proportion of juvenile wood in each board to determine its radial position.

A bark-to-bark strip in north-south direction was cut out of each disk. Each strip was sanded and scanned using an optical scanner with a resolution of 1200 pixels per inch. The resulting images were analyzed and the ring widths measured using the R package *measuRing* (Lara et al. 2015). To determine whether the sample trees were representative for the thinning status of the stand, growth releases were identified for each of them using growth increase events on an individual tree-level with the R package *pointRes* (van der Maaten-Theunissen et al. 2015), specifically by using a moving window normalization with the Neuwirth method (Neuwirth et al. 2007). A growth release event is defined by a remarkable growth increase in the analyzed year compared to the radial growth in previous years at an individual-tree level (Schweingruber et al. 1990). On average, the sample trees from thinned stands exhibited more growth releases than those from unthinned stands across all three species. Mean tree ring widths determined on the bottom disks are displayed in Table 1.

2.3 Board-level measurements

A total of 119 logs were sawn into structural timber with cross-sectional dimensions of 45 mm × 100 mm, yielding 1342 pieces. Timber was then kiln dried and scanned using the GoldenEye 702 (Microtec, Brixen, Italy) giving an overall knottiness value for each board using the X-ray technology. The obtained knottiness value is dependent on the size and position of knots relative to the width of each board. As such, it is a good approximation of the knot area ratio (KAR). This was confirmed when comparing the values to the results of visual inspection (Rais et al. 2014). Rais et al. (2014) found that both values showed similar trends between different planting densities, indicating the usefulness of the knottiness values obtained with the X-ray technology. The relationship between board knottiness and bending strength was previously also confirmed by Nocetti et al. (2010), where an increase in board knottiness led to decrease in bending strength. Following the assessment of knottiness using the GoldenEye 702, the timber was transported to the NUI Galway laboratories where it was stored in a conditioning chamber at 20 °C and 65% relative humidity until constant mass was attained.

All boards were tested in four-point bending in accordance with EN 408 (CEN 2012), and the global modulus of elasticity (E_m) and bending strength (f_m) were calculated using recorded data and equations from the standard. Density (ρ) was determined on a defect-free section of timber cut as close as possible to the fracture location and measured immediately after testing. Moisture content was determined using the oven dry method as per EN 13183-1 (CEN 2002). All tested properties were adjusted to 12% moisture content using the equations provided by EN 384 (CEN 2010). A 300-mm-long section was cut as close as possible to the fracture location, from which a small clear specimen with the dimensions of 20 mm × 20 mm × 300 mm was cut using a band saw. A total of 1303 small clear specimens were destructively tested in a three-point bending test as per BS 373 (British Standards Institution 1957) and the modulus of elasticity, bending strength, and density were determined using the equations provided by the standard.

2.4 Data analysis

The data were analyzed using the open-source statistical environment R (R Core Team 2018). A Bayesian data analysis was performed using a multilevel model (also known as a hierarchical or mixed-effects model) to compare the measured properties of the boards from thinned stands to those from unthinned stands, as it allows the incorporation of uncertainty in the model (Gelman et al. 2004; Kruschke 2014). The model was implemented in Stan (Carpenter et al. 2017; Stan Development Team 2018) using the R package *brms* (Bürkner 2017) to assess the effect of thinning on the mechanical properties. Stan uses Markov chain Monte Carlo sampling to draw a sample from the posterior distribution, which is then used for inference.

The following explanatory variables were used in the analysis: thinning (levels-no thinning, thinned), radial position within a log (levels-no juvenile wood, less than 50%, more than 50%), pith presence (levels-no pith, pith present), and longitudinal position within a tree (levels-first log, second log). They were dummy coded using as reference a Sitka spruce board from the bottom log with no juvenile wood or pith coming from a co-dominant tree from an unthinned stand.

An interaction between the species and thinning was included in the model. Species and crown social class were added as group-level effects (random effects), as were the nested effects of stand, plot-in-stand, and tree-in-plot-in-stand on the model intercept in accordance with the experiment design. Model priors are weakly informative and are based on previously reported values (Table 2). All models were manually checked for convergence and effective numbers of samples with multiple short chains followed with one longer chain used for inference (McElreath 2016).

To quantify the evidence strength of the effect of thinning, Bayes factors were used (Gelman et al. 2004; Kruschke 2014). They were computed as ratios of posterior probability under the hypothesis that thinning negatively impacts the examined properties against the alternative that thinning leads to an increase in them. For example, an 80% probability that thinning reduces some characteristic (probability of alternative = 20%) gives a Bayes factor of 4. This enables the evaluation of conclusions with regard to the strength of evidence in a more objective way than tests of significance.

3 Results

3.1 Data overview

Table 3 shows the mechanical properties and density for each species from the tests on structural-sized timber and small clear specimens. Timber quality varied between species and thinning regime in both structural-sized timber and small clear specimens. Boards of Douglas fir and Norway spruce showed an overall decrease in both the modulus of elasticity and bending strength with thinning, while they increase for Sitka spruce. Density appears to decrease with thinning in Norway spruce, increase in Sitka spruce, and remains the same in Douglas fir. Although modulus of elasticity measured on small clear specimens was in all cases lower than when measured on structural-sized timber, the differences between unthinned stands and thinned stands were similar. The populations of boards as such were not directly representative for each stand due to the skewed proportions of crown social classes and the different numbers of boards per log. As such, the differences presented in Table 3 are not to be interpreted on their own, without using a multilevel model.

The strength classes of timber determined by the characteristic values calculated according to EN 338 (CEN 2016) differed between unthinned and thinned stands. They varied from unthinned to thinned stands as follows: Douglas fir C30 to C27, Norway spruce C22 to C18, and Sitka spruce C16 to C18.

One possible explanation for the differences between timber from the different thinning regimes suggested by the past studies is the influence of the proportion and size of knots on the mechanical properties (Auty et al. 2012). Thinning leads to more growing space, which should result in an increase in the size of crowns and consequently the branch sizes to support bigger crowns, as shown in a review by Pretzsch and Rais (2016). However, opposite trends were found in this study across the three species (Fig. 1) (see Chapter 4).

To allow for a better understanding of the relationship between bending strength and knottiness, the relationship was further examined (Fig. 2) and a linear regression was fitted to the points. A relatively low value of R^2 was observed (R^2 =

Table 2 Multilevel models—prior distributions

Model parameter	Intercept	Population-level effects	Standard deviations of group-level effects
Structural-sized timber			
E_m	*Normal(10,000.2500)*	*Normal* (0.2500)	*Student t*(3, 0, 2163)
f_m	*Normal(50.10)*	*Normal* (0.10)	*Student t*(3, 0, 14)
P	*Normal(450.50)*	*Normal* (0.50)	*Student t*(3, 0, 69)
Small clear specimens			
E_m	*Normal(9000.2000)*	*Normal*(0.2000)	*Student t*(3, 0, 2110)
f_m	*Normal(75.10)*	*Normal*(0.10)	*Student t*(3, 0, 18)
ρ	*Normal(450.50)*	*Normal*(0.50)	*Student t*(3, 0, 79)
Specific properties of boards			
E_m/ρ	*Normal*(20.5)	*Normal*(0.5)	*Student t*(3, 0, 10)
f_m/ρ	*Normal*(100.25)	*Normal*(0.25)	*Student t*(3, 0, 26)
Specific properties of clears			
E_m/ρ	*Normal(20.5)*	*Normal*(0.5)	*Student t*(3, 0, 10)
f_m/ρ	*Normal(160.15)*	*Normal*(0.10)	*Student t*(3, 0, 20)
Acoustic velocity			
Velocity	*Normal(4000.250)*	*Normal*(0.250)	*Student t*(3, 0, 357)

Table 3 Timber and wood properties by species and thinning regime—mean values, standard deviation in brackets

	Structural sized timber				Small clear specimens			
	N	E_m	f_m	ρ	N	*E*	f_m	ρ
Douglas fir								
Unthinned	108	12,985 (1944)	59 (15)	562 (47)	107	11,200 (1474)	99 (13)	565 (46)
Thinned	163	11,961 (1907)	55 (17)	562 (50)	161	10,799 (1718)	99 (16)	565 (50)
Norway spruce								
Unthinned	118	10,465 (1509)	49 (10)	470 (51)	118	9402 (1967)	79 (14)	485 (54)
Thinned	250	9023 (1796)	41 (13)	420 (46)	249	7672 (1549)	65 (13)	420 (56)
Sitka spruce								
Unthinned	335	9570 (1892)	47 (13)	421 (35)	302	7880 (1519)	66 (11)	423 (45)
Thinned	368	10,192 (1822)	50 (12)	451 (56)	366	8341 (1734)	69 (15)	453 (63)

Modulus of elasticity (E_m) and bending strength (f_m) in MPa, density (ρ) in kg m^{-3}

0.22), implying that knottiness by itself is not an ideal predictor of bending strength in boards.

3.2 Multilevel modeling

Table 4 shows the results of the multilevel modeling on each of the studied properties across the two specimen sizes, and the model standard errors are given in Table 5. All three properties in general decreased with thinning in structural-sized boards and small clear specimens, the effect being, however, species dependent. For both specimen sizes, the studied properties decreased with increasing proportion of juvenile wood. Pith presence appeared to have a negligible effect, while the effect of longitudinal position varied among the properties and specimen sizes. Increasing board knottiness reduced modulus of elasticity at a similar rate to bending strength.

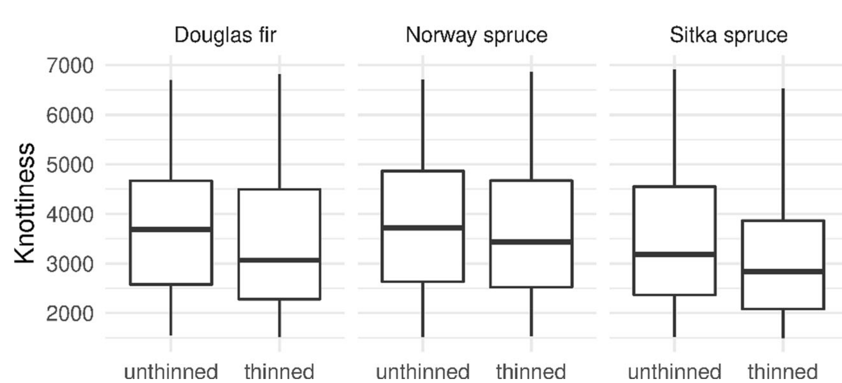
Bayes factors for the hypothesis that thinning negatively affects the mechanical properties and density are given for each species in Table 6. In the current dataset, thinning was more likely to reduce the examined properties than to have no effect or to increase them. Though the likelihood varied across the properties and the specimen sizes, a stronger evidence was shown for the negative effect. Sitka spruce was the least likely to be negatively affected by thinning, as the evidence with regard to grade-determining properties was relatively inconclusive.

3.3 The magnitude of the effect of thinning

Even though the mechanical properties and density are correlated, the size of the thinning effect will likely differ between the individual properties, as they are not necessarily influenced by the same factors in the same way. Therefore, the effects of thinning and their magnitude were examined accounting for underlying differences in wood density using two derived material properties, the specific stiffness, and specific strength. They are commonly used to describe materials where weight is the limiting factor and are also known as stiffness-to-weight and strength-to-weight ratios, calculated as ratios of individual properties divided by density of individual specimens (Zhang et al. 2011). By doing so, the differences in density and elastic modulus or bending strength are accounted for at the same time. This enables an improved estimation of the magnitude of the effect.

When looking at the specific mechanical properties of small clear specimens (Table 7), the effects of thinning were the same across different species. Thinning led to a decrease in

Fig. 1 Board knottiness value according to X-ray measurement by species and thinning regime



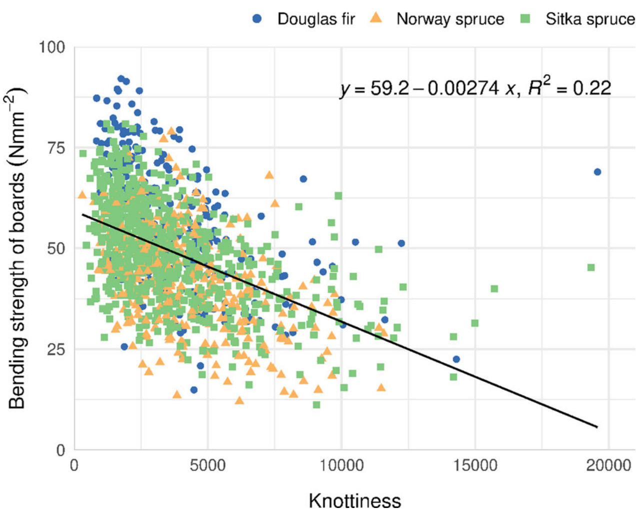


Fig. 2 Bending strength and board knottiness value according to X-ray measurement

both specific stiffness and specific strength. The results showed that while thinning impacts both specific stiffness and specific strength, the impact is different to that found when considering the three properties (E_m, f_m, ρ) separately. The effects were again different between specimen sizes, suggesting that the relationships between properties change when looking at timber quality of defect-free samples instead of sawn timber. The impact of thinning was estimated using multilevel models, where the dependent variables were both specific properties across both specimen sizes, while independent variables remained the same as in the previous models. To better illustrate the size effects, the differences are shown in terms of percentage based on posterior distributions for each species across the four models (Fig. 3).

Compared to unthinned stands, thinning is likely to reduce both the specific stiffness and strength (Fig. 3), in line with the previous findings. The size of effect is relatively small, the mean being less than 5% and rarely exceeding 20%. Of the three species, Sitka spruce seems to be the least affected by thinning with a negligible drop in specific stiffness and strength, while Norway spruce and Douglas fir exhibit a stronger drop in the quality.

3.4 Stand-level validation

To test whether the effect of thinning on sawn timber matches the effect found on standing trees, the relationship between thinning status and longitudinal acoustic velocity of individual trees was examined on the full sample of trees ($N = 487$). Acoustic velocity was reported to be a relatively good indicator of overall tree stiffness and has been used to approximate the dynamic modulus of elasticity of individual trees (Lindström et al. 2009; Simic et al. 2018). The overall means and standard deviations of longitudinal acoustic velocity can be seen in Table 8.

Table 4 The effect of thinning, radial and longitudinal position, pith presence, and knots on grade-determining properties, model standard errors in Table 5

	Structural sized timber			Small clear specimens		
	E_m	f_m	ρ	E_m	f_m	ρ
General						
Intercept[a]	11,780	62	489	8900	81	484
$\rho_{residual}$	1242	10	32	1415	11	42
Proportion of juvenile wood						
< 50%	− 391	− 4	− 34	− 362	− 5	− 20
> 50%	− 780	− 5	− 54	− 727	− 8	− 47
Pith presence						
Present	− 186	1	− 11	n/a	n/a	n/a
Longitudinal position						
Second log	468	−2	− 3	490	0.4	2
Knottiness						
Knottiness	− 0.3	− 0.002	n/a	n/a	n/a	n/a
Thinning regime						
Thinned, SS	− 150	− 1	5	98	− 0.8	4
Unthinned, DF	1754	6	34	1381	5	32
Thinned, DF	903	2	22	862	4	22
Unthinned, NS	250	0.1	11	502	3	16
Thinned, NS	− 562	− 4	− 24	− 720	− 5	− 26
Group-level effects						
$\rho_{crown\ class}$	294	2	10	294	2	9
$\rho_{species}$	1261	6	56	1199	14	56
ρ_{stand}	927	4	32	866	7	34
$\rho_{plot\ in\ stand}$	287	2	11	258	3	12
$\rho_{tree\ in\ plot\ in\ stand}$	1064	6	32	892	8	34

Modulus of elasticity (E_m) and bending strength (f_m) in MPa, density (ρ) in kg m^{-3}

[a] Reference level: unthinned Sitka spruce, no juvenile wood or pith, first log

To examine how thinning affects longitudinal acoustic velocity, another multilevel model was applied for the 487 sample trees. The population level effects included species and thinning along with their interaction, and group-level effects of crown class, site, and plot-in-site in the model. The model priors were weakly informative, which means that the developed multilevel model was mostly influenced by the data inputted in the model and not prior coefficient distributions (Table 2). The results matched with what was found on sawn timber: thinning very likely reduces the longitudinal velocity in Douglas fir and Sitka spruce (Bayes factors of 4.5 and 3.3, respectively), showing a decrease in overall stiffness of trees. The evidence of the effect of thinning in Norway spruce was more inconclusive (Bayes factors of 1.2), showing that the relationships are again species-dependent. The size of effect was similar to that found in the specific mechanical properties: on average, thinning reduced dynamic stiffness by less than 5%, with losses rarely exceeding 15%.

Table 5 Multilevel models for the different grade-determining properties in structural sized timber and small clear specimens—parameter standard errors

	Structural-sized timber			Small clear specimens		
	E_m	f_m	ρ	E_m	f_m	ρ
Intercept						
Intercept[a]	1240	5.6	36	1126	7.9	37
$\rho_{residual}$	25	0.2	0.63	28	0.23	0.83
Proportion of juvenile wood						
< 50%	96	0.76	2.3	104	0.83	3.1
> 50%	110	0.88	2.4	100	0.81	3
Pith presence						
Present	135	1.1	3.4	n/a	n/a	n/a
Longitudinal position						
Second log	69	0.57	1.8	79	0.64	2.3
Knottiness						
Knottiness	0.02	0.00016	n/a	n/a	n/a	n/a
Thinning regime						
Thinned, SS	1105	4.9	30	1000	6.2	31
Unthinned, DF	1656	6.8	43	1430	8.6	42
Thinned, DF	1608	6.7	43	1428	8.6	42
Unthinned, NS	1506	6.4	39	1327	8.1	40
Thinned, NS	1484	6.5	39	1297	8	39
Group-level effects						
$\rho_{crown\ class}$	272	1.7	9.3	274	1.9	9.5
$\rho_{species}$	1158	5.6	39	1022	9.2	40
ρ_{stand}	807	3.9	26	740	5.9	28
$\rho_{plot\ in\ stand}$	241	1.3	8.8	215	2.1	9.2
$\rho_{tree\ in\ plot\ in\ stand}$	120	0.73	3.5	109	0.92	3.8

Modulus of elasticity (E_m) and bending strength (f_m) in MPa, density (ρ) in kg m^{-3}

[a] Reference level: unthinned Sitka spruce, no juvenile wood or pith, first log

4 Discussion

Compared with the findings of previous studies (Roblot et al. 2008; Henin et al. 2018; Moore et al. 2009; Simic et al. 2018; Gardiner et al. 2011; Larsson et al. 1998; Wilhelmsson and Arlinger 2002) on the same species, all of the measured physical and mechanical properties were relatively high. All sample trees in this study from thinned stands represented final crop trees; therefore, the best material available at the end of the rotation of the stands due to the type of thinning implemented, which was thinning from below with systematic row thinning. Thinning from below usually removes trees of a lesser quality, and this is reflected in the final stand composition. Elastic moduli obtained from the small clear specimens were lower than those from boards, which is most likely due to the difference in the test setup between the two specimen sizes (Brancheriau et al. 2002), and relatively high heterogeneity of timber within a single board. Bending strengths were considerably higher in small clear specimens, likely due to the absence of knots and other unmeasured properties (slope of grain, microfibril angle, etc.). Densities were almost identical for the different sizes of specimens, as they were both determined on defect-free sections close to the fracture position.

Table 6 Bayes factors for the effects of thinning across the three species, wood properties and specimen sizes

	Structural sized timber			Small clear specimens		
	E_m	f_m	ρ	E_m	f_m	ρ
Douglas fir	2.8	2.3	1.8	2.1	1.3	1.6
Norway spruce	2.7	2.8	3.9	4.7	4.0	4.6
Sitka spruce	1.2	1.6	0.7	0.7	1.2	0.7

Table 7 Specific stiffness and specific strength by species and thinning regime—mean values, standard deviation in brackets

	Structural sized timber		Small clear specimens	
	E_m/ρ	f_m/ρ	E_m/ρ	f_m/ρ
Douglas fir				
Unthinned	23 (3)	104 (22)	20 (2)	176 (18)
Thinned	21 (3)	96 (27)	19 (2)	174 (21)
Norway spruce				
Unthinned	22 (2)	103 (18)	19 (3)	163 (20)
Thinned	21 (3)	94 (25)	18 (2)	154 (20)
Sitka spruce				
Unthinned	22 (4)	107 (27)	19 (2)	156 (17)
Thinned	22 (4)	109 (22)	18 (3)	152 (21)

Specific stiffness (E_m/ρ) in 10^6 m^2 s^{-2}, specific strength (f_m/ρ) in 10^3 m^2 s^{-2}

Figure 1 appears to imply that thinning is likely to lead to a decrease in overall knottiness in sawn timber. However, this observation does not suggest a cause-effect relationship. The difference in knottiness between the boards from each thinning regime was most likely a consequence of two interacting factors: (a) bigger diameter logs from the thinned stands compared with unthinned stands, leading to different proportions of boards with knots, and (b) the type of thinning carried out (from below with added systematic thinning of rows).

When comparing the timber from the three studied species, the following observations could be made. Douglas fir timber had substantially better mechanical properties than the timber from both spruce species in both thinned and unthinned stands. Timber from unthinned Norway spruce stands had better mechanical properties than timber from unthinned Sitka spruce stands, while an opposite trend could be found in thinned stands, in both specimen sizes.

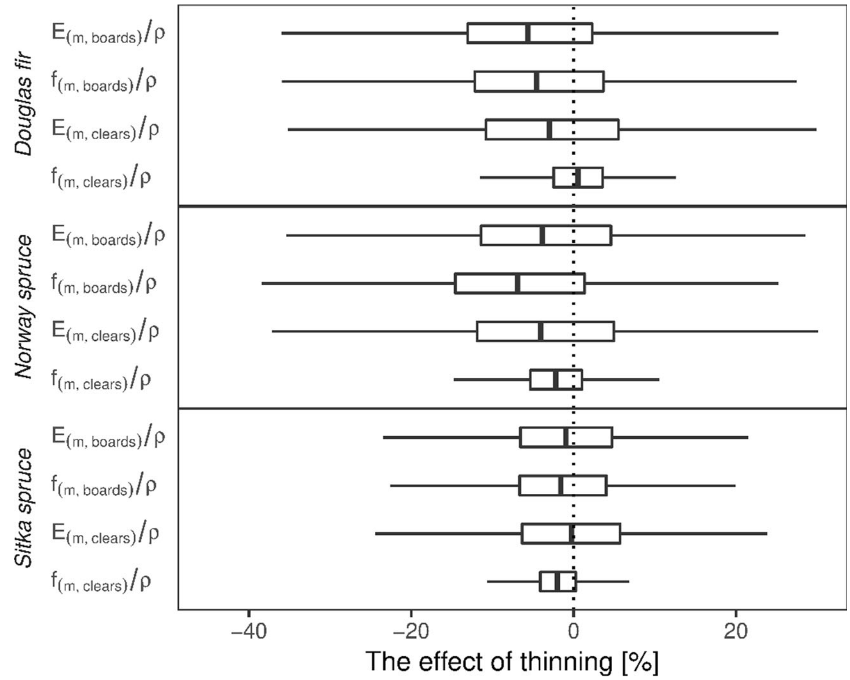


Fig. 3 The effect of thinning on specific mechanical properties across the species and two specimen sizes

The presence of juvenile wood lowers all grade-determining properties, in line with previous studies on softwoods (Brüchert et al. 2000; Henin et al. 2018; Cameron et al. 2015). Although the longitudinal position of the sample had effects on wood properties, the direction of the effects in this study was not as uniform as in previous studies (Brüchert et al. 2000; Lindström et al. 2009; Rais et al. 2014; Simic et al. 2018). This was likely due to the fact that in the current study, only two logs per tree were taken and the effect would be more pronounced with increasing number of logs per tree. Knottiness reduced both the elastic modulus and the bending strength of structural-sized boards similarly (Table 4).

Thinning reduced all three grade-determining properties with likelihood varying between species. While there appeared a relatively strong evidence of this relationship in Douglas fir and Norway spruce, the evidence in Sitka spruce was more inconclusive. The relationships were similar when looking at specific mechanical properties. The specific properties were lower in thinned stands, which implies that density is affected by thinning at a different rate than the elastic modulus or bending strength. One possible explanation for this could be related to the microstructure of wood. It has been shown that thinning affects tracheid lengths (e.g., Jaakkola et al. (2005b)), which could explain the different rates of changes across properties. As the impact of thinning was confirmed on both structural-sized boards (with knots) and in small clear samples (without knots), the differences in mechanical properties due to thinning cannot be attributed solely to the different crown development as a result of or lack of thinning. Although there is little doubt that thinning can influence the branchiness of the logs and as a result the knottiness of the sawn timber (see Pretzsch and Rais 2016), the results of the current study indicated that significant differences are also present in the microstructure of wood. This was partly confirmed in the current study, as the mean ring width was found to be lower in trees from unthinned stands than in trees from thinned stands.

The observation that thinning reduces timber quality was also supported by the analysis carried out on standing trees on an almost 10 times bigger sample using longitudinal velocity as a proxy to estimate tree stiffness. Although in standing trees there appeared a significant evidence of this trend in Douglas fir and Sitka spruce, no such conclusion was supported for Norway spruce. The size of the effect was also relatively small and depended on the species, in most cases, reducing the measured properties by less than 5%.

The difference in evidence strength of the effect of thinning between standing trees and sawn timber could be attributed to the relatively large heterogeneity found in boards from the same tree or between trees of the same species in the same stand. Irrespective of the source of this difference in significance, the trends found were the same across the studied species both when comparing the acoustic velocities of individual trees or when examining the sawn timber from those trees.

Table 8 Longitudinal velocity by species and thinning regime

	Douglas fir			Norway spruce			Sitka spruce		
	N	Mean	SD	*N*	Mean	SD	*N*	Mean	SD
Unthinned	85	4167	299	125	3989	357	45	3847	366
Thinned	60	3727	300	88	3905	327	84	4007	304

Velocity in ms^{-2}

5 Conclusions

All three implemented approaches (mechanical testing of sawn timber, mechanical testing of small clear specimens, and acoustic velocity in standing trees) have shown a similar response to thinning with a varying size of the effect. This shows that while the direction of the effect can be more or less accurately described by any of the approaches, the estimations of size of the effect can vary due to the different approach. However, if future studies confirm and quantify the differences between approaches, any of them could potentially be used for quantification of the effect that a certain factor (such as thinning) can have on mechanical properties. The ratios of both stiffness and strength to density were more stable than the three grade-determining properties across various factors; therefore, their use can be recommended in future studies of structural timber quality. Additionally, the results of the current study indicate that further research is required on the effect thinning has on the microstructure of wood.

With regard to optimizing silviculture for timber quality, there are no uniform conclusions. Overall, Sitka spruce is the least affected by thinning out of the three studied species. With this in mind, thinning of Sitka spruce stands could be recommended, as it maximizes the volume production with a minimum trade-off in the loss of quality of the end product. Douglas fir in the current study came from a site with a relatively low productivity and exhibited similar trends to the other two species. It is unclear whether the differences in the magnitude of the effect can solely be attributed to the difference among species, as they could also be affected by between-pairs difference in site productivity of the selected stands. Setting this potential interaction aside, the effect of thinning still appears to be more likely negative for timber quality, with a varying magnitude. Due to time and cost constraints, other potential factors from genetics to other silvicultural interventions were intentionally excluded from the current study. Even though the current study included the effect of crown social classes by treating them as a random effect, more targeted research is needed on the relationships between various crown properties along with other changes in trees caused by different thinning regimes, and mechanical properties of the timber produced.

The results of the current study confirmed that there is a trade-off between tree growth and timber quality in softwoods caused by thinning. The exact nature of this trade-off depends on various factors while remaining obviously relatively small in general regarding the studied species. As the strength grade of structural-sized timber is usually limited by one of the three grade-determining properties (i.e., density, stiffness and strength), a relatively small change in the limiting property can influence the strength grade of the produced timber. On account of this asymmetrical relationship, the changes in mechanical properties due to thinnings are not negligible by default, as they can lead to a lower strength grade of the timber produced. Whether it becomes important depends on the aims and limitations of managing individual stands, using applied silviculture to balance out the different demands with what is achievable in the forest environment.

Acknowledgements The authors would like to thank Coillte and the Irish Forestry Unit Trust for enabling access to the forest stands and providing the testing material. The use of GoldenEye-702 machine was kindly provided by the Murray Timber Group while Martin Bacher from MiCROTEC helped with the scanning of the boards.

Funding The first author was supported in undertaking this work by a Teagasc Walsh Fellowship. This work was also supported by grant aid from the Forest Sector Development Division of the Department of Agriculture, Food and the Marine, Ireland.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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