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ORIGINAL PAPER

Distribution of the timber quality attribute 'knot surface' in logs of *Fagus sylvatica* L. from pure and mixed forest stands

Kirsten Höwler[1] · **Torsten Vor**[1] · **Peter Schall**[1] · **Peter Annighöfer**[2] · **Dominik Seidel**[1] · **Christian Ammer**[1]

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Abstract

Research on mixed forests has mostly focused on tree growth and productivity, or resistance and resilience in changing climate conditions, but only rarely on the effects of tree species mixing on timber quality. In particular, it is still unclear whether the numerous positive effects of mixed forests on productivity and stability come at the expense of timber quality. In this study, we used photographs of sawn boards from 90 European beech (*Fagus sylvatica* L.) trees of mixed and pure forest stands to analyze internal timber quality through the quality indicator *knot surface* that was quantitatively assessed using the software Datinf® Measure. We observed a decrease in *knot surface* with increasing distance from the pith as well as smaller values in the lower log sections. Regarding the influence of neighborhood species identity, we found only minor effects meaning that timber qualities in mixed stands of beech and Norway spruce (*Picea abies* (L.) H. Karst.) tended to be slightly worse compared to pure beech stands.

Keywords Deciduous timber · European beech · Forest conversion · Knottiness

Introduction

Throughout the twentieth century, forest management has perfected commercial timber production in forest stands consisting of only one tree species (Puettmann et al. 2012). As a result, even in areas that are naturally rich in tree species, a few species grown in monocultures dominate the picture (Bauhus et al. 2017a, b). This development was driven by simpler planning, easy silvicultural operations, and the high predictability of the (wooden) products obtained by even-aged monospecific forest management (Bauhus et al. 2017a). However, in the past two decades there has been an increased focus on exploring advantages and disadvantages of mixing species regarding productivity and timber quality in commercial forests, as well as operational challenges (Knoke et al. 2008; Bauhus et al. 2017a; Bravo-Oviedo et al. 2018; Messier et al. 2019). Monospecific stands are, with a few exceptions (see Hobi et al. 2015), rare in natural forests and thus are mostly a sign of anthropogenic activities. Such monospecific stands also seem to be more susceptible to abiotic and biotic stressors (Bauhus et al. 2017a). Nowadays, silvicultural activities are aiming at creating more diverse and more structured forest stands across Europe. As a result, the proportion of single-species forest stands has steadily decreased due to forest conversion in favor of more heterogeneous mixed forest stands (FAO 2001; von Lüpke et al. 2004; Forest Europe 2015; Pach et al. 2018). Many European countries started to convert pure coniferous forests into mixed and deciduous forests a few decades ago and this conversion is currently still ongoing due to changed forest policies (von Lüpke et al. 2004; Ammer et al. 2008; Forest Europe 2015). Mixed forest stands are considered to promote biological and structural diversity (Knoke et al. 2008; Bauhus et al. 2017a; Ampoorter et al. 2020), can enhance productivity (e.g., Vilà et al. 2007; Pretzsch and Schütze 2009; Paquette and Messier 2011; Pretzsch et al. 2015; Ammer 2019), and offer greater ecological and economic stability and resilience under changing and uncertain future climate conditions (von Lüpke et al. 2004; Millar et al. 2007;

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✉ Kirsten Höwler
kirsten.hoewler@forst.uni-goettingen.de

[1] Silviculture and Forest Ecology of the Temperate Zones, Faculty of Forest Sciences, University of Göttingen, Büsgenweg 1, 37077 Göttingen, Germany

[2] Forest and Agroforest Systems, Technical University of Munich (TUM), Hans-Carl-von-Carlowitz-Platz 2, 85354 Freising, Germany

Knoke et al. 2008; Knoke and Seifert 2008). While the knowledge on growth, nutrient cycling, and other ecosystem functions of mixed forests has strongly improved, much less is known about timber quality, i.e., whether the mentioned advantages of mixed forests come at the expense of timber quality. In particular, with regard to upcoming changes on the timber market (e.g., higher availability of deciduous trees and lower availability of coniferous trees; e.g., Dill-Langer and Aicher 2014; Orazio et al. 2017), mixed neighborhood effects on deciduous timber quality (e.g., for European beech) need to be investigated more intensely. Currently, only about half of the sustainable annual growth production and thus wood utilization potential of several deciduous tree species is being harvested and used (Lorenz et al. 2018). In Europe, out of approximately 800 million m^3 of roundwood in 2018, coniferous roundwood accounted for around 71% (calculated from FAOSTAT data; FAO 2020). Industrial roundwood (coniferous and deciduous) accounted for about 80% and wood fuel (coniferous and deciduous) for about 20% of the total roundwood. However, the shares of coniferous and deciduous timber vary considerably: While approximately 80% of coniferous timber is used for industrial roundwood, about 62% of deciduous timber is used as wood fuel (calculated from FAOSTAT data; FAO 2020). This means that only a small amount of the harvested deciduous timber is used for high-quality material in the first processing stage. These differences in timber usage are not primarily a result of supply but of processing capabilities (Ammann et al. 2016; Konnerth et al. 2016; Aicher et al. 2018), consumers preferences (Gartner 2005; Knoke et al. 2006) and different wood properties (Spellmann 2005). Coniferous and deciduous timber differ in anatomical structure and complexity (e.g., Matyssek et al. 2010). This results in different physical, mechanical, and chemical properties observed in hardwood when compared to coniferous timber. All these factors may explain why a substitution of coniferous timber by deciduous timber is currently underexplored and underrepresented (Schier et al. 2018). So, developing an understanding of where the potential for substitution exists and which factors influence deciduous timber quality is of crucial importance. It seems neither ecologically nor economically sustainable to use such a high proportion of potentially valuable timber for energy purposes only (Dill-Langer and Aicher 2014).

In general, the timber quality of a stem is affected by the tree's neighborhood and resulting competition (Höwler et al. 2017; Burkardt et al. 2019). With an increasing species diversity in mixed forest stands, the diversity of the competitive environment also increases and with this, the potential effects on timber quality. On the one hand, mixed forest stands are of higher structural heterogeneity compared to monospecific forest stands (Juchheim et al. 2019). This may increase the variability in stem and crown form, stem taper, stem bending or straightness, number of branches and branch dimensions, or the range of wood properties in general, all leading to changed timber quality (Bayer et al. 2013; Pretzsch and Rais 2016; Bauhus et al. 2017b; Benneter et al. 2018). On the other hand, admixed tree species may also serve as trainer trees to foster self-pruning of the lower and most valuable stem section on crop trees and consequently improve timber quality (Bauhus et al. 2017b). Moreover, timber quality is also influenced by the silvicultural treatments applied during the whole rotation cycle such as for example pruning, pre-commercial, and commercial thinning. In summary, the effect of mixed-species neighborhoods on the timber quality of a target tree can be expected to depend on species interactions, competitive capacity, species composition, and silvicultural regime or treatment (Bauhus et al. 2017b; Benneter et al. 2018). One of the most important features for timber quality is the amount, condition, and size of knots. According to European grading standards, a single knot could downgrade an entire log (Deutsches Institut für Normung e. V. 2011; Deutsches Institut für Normung e. V. 2013) due to its effects on mechanical, physical, and aesthetic properties of timber (Torkaman et al. 2018). Because of discontinuities and deviations in anatomical structure, knots cause a reduction in strength and stiffness as well as changes in swelling and shrinking behavior of timber (Osborne and Maguire 2016; Richter 2019). To a certain degree, silvicultural management can be applied to control the amount, condition, and size of branches. For example, branch size and self-pruning can be influenced by maintaining high densities in early stand development phases (e.g., Hein 2008). After this 'qualification phase', accelerated diameter increment can be fostered by crown release (e.g., Hein 2008). As small branches are more rapidly occluded compared to large branches, the resulting knotty core inside the log is also smaller (O'Hara 2007; Kint et al. 2010). Forest management therefore often seeks to minimize the branch diameter and branch occlusion period (Hein 2008). This study aims at expanding the understanding of mixed forest dynamics by focusing on timber quality in mixtures. We evaluated and compared tree logs from mixed and pure stands for one of the most important Central European tree species (Knoke 2003), European beech (*Fagus sylvatica* L.). Our primary research questions were:

1. How is the timber quality attribute *knot surface* distributed along the horizontal and vertical stem axis of European beech trees?
2. How does neighborhood species identity affect the timber quality attribute *knot surface* of European beech trees?

We hypothesized that (i) the timber quality attribute *knot surface* increases along the vertical stem axis (from bottom to top) and decreases along the horizontal stem axis (from pith to bark) as a result of the applied silvicultural treatment. We further hypothesized that (ii) the timber quality attribute *knot surface* is smaller in pure compared to mixed beech stands due to higher competition intensity of beech itself. For simplicity, we have used the term ‘timber quality’ in this study to refer to all negative and positive internal and external stem, wood or timber properties.

Methods

The horizontal and vertical distribution of the timber quality attribute *knot surface* (cf. Eq. 1) and the effect of the identity of neighboring tree species on timber quality of European beech were investigated using 90 European beech sample trees from four *forest mixture types* (Table 1). The criteria for the selection of sample trees were (i) tree classes 1–3 (dominant to co-dominant) according to Kraft (1884) and (ii) a diameter at breast height (DBH, at 1.3 m) between 35 and 50 cm. Additionally, these beech sample trees (iii) had at least two major (dominant or co-dominant) competitors either from the same species (pure beech stands) or from the admixed tree species (mixed beech stands). Whether a neighboring tree was classified as a major competitor depended on its size compared to the size of the target tree (Tomé and Burkhart 1989): all neighboring trees with a similar or larger DBH and a similar tree height were therefore classified as main competitors.

All sample trees were harvested during a commercial harvest of the forest district Reinhausen (Niedersächsische Landesforsten, Germany). Subsequently, the trees were sawn into 180 log sections of differing length (min. 3 m, max. 5 m) and eventually to 1900 boards of differing thickness (min. 20 mm, max. 50 mm) according to the standard commercial sawing procedure of the cooperating sawmill (Fehrensen GmbH, private limited company, Hann. Münden, Germany; cf. Table 2). For this study, we analyzed the boards of the first two log Sects. (6–10 m height in total) of each sample tree, as the first 10 m account for approximately 80% of the deciduous timber value (Bachmann 1970; Kint et al. 2010).

Each board was photographed lengthwise using a single-lens reflex camera (Pentax K10D), which was mounted on a tripod. This ensured that each photograph was taken at the same angle (90°) and the same distance (1 m) to the board (Fig. 1).

The number of photographs taken per board varied between three and five due to differences in total lengths of the boards. Therefore, all photographs of each individual board were manually merged using the software CorelDRAW © X4 (version 14.0.0.567, Corel Corporation 2008). Subsequently, a quantitative timber quality measurement was conducted using the software Datinf® Measure (version 2.2, Datinf GmbH, Tübingen, Germany). Datinf® Measure is a software to measure surfaces or lengths on, e.g., photographs and uses vector-based measuring tools. For a successful measurement, a scale that was provided through a measuring tape on every photograph enabled the conversion of pixel into metric units. Then, the ‘distance’ tool of the software was applied to measure the board length as well as the board width (assessed every 50 cm). Correspondingly, all surfaces were assessed using the ‘polygon’ tool of the software (Fig. 2). This included the total board surface (without bark), but also the quality attribute *knot surface*, which is considered an indicator of knottiness (Höwler et al. 2019). The position on the measuring tape was assigned to each measured object to obtain information about the height above the forest floor (see Höwler et al. 2019 for further methodological details).

The logs were virtually divided into (i) board groups according to the *distance to the central board* to analyze the distribution of quality attributes along the horizontal stem axis for the lower (upper end at min. 3 m, max. 5 m height) and upper (upper end at min. 6 m, max. 10 m height) log sections and into (ii) height strata of 50 cm to investigate the distribution of quality attributes along the vertical stem axis (see Fig. 3).

Horizontal distribution of knot surface

The horizontal distribution of the timber quality attribute *knot surface* from pith to bark was analyzed separately for the lower (3–5 m height) and upper log Sects. (6–10 m height), because the number of boards was higher for the lower sections due to stem taper. The number of boards per log section was determined for each sample tree (lower log sections: min. 6 boards, max. 17 boards; upper log sections: min. 6 boards, max. 15 boards) to define the central board as a measure of pith within the log sections. If there was an uneven number of boards within a log section, the median board was marked as the central board. If there was an even number of boards, the central board was calculated using the mean of the two middle boards of the log section. A number was assigned to each board to group them by *distance to the central board*, starting from the central board (group 0). The number for a particular group of boards was multiplied by the board thickness (min. 21 mm, max. 50 mm) to calculate the distance of the boards from the determined center of the logs. Offcuts were excluded from this study so that the maximum radius of the logs was 200 mm.

Vertical distribution of knot surface

The lower (3–5 m height) and upper (6–10 m height) log sections of each sample tree were merged to investigate the vertical distribution of the timber quality attribute *knot*

Table 1 Description of the study sites from the forest districts Ebergötzen, Reinhausen, and Sattenhausen based on Höwler et al. (2017)

Location (degree, minutes, seconds)		Ebergötzen		Reinhausen								Sattenhausen			
		51°40′55.5″N 10°04′56.9″E		51°26′55.9″N 10°00′52.0″E								51°30′41.7″N 10°04′15.8″E			
Site condition		Triassic sandstone		Triassic sandstone								Triassic limestone			
Elevation [m a.s.l.]		151–200	151–200	301–350	251–300	251–300	251–300	251–300	251–300	251–300	251–300	251–300	301–350	351–400	251–300
Department		1065	1068	10	14	14	16	18a	18e	34	37	1024	1033	1039	1043
Area [ha]		6.2	4.0	14.6	13.9	13.9	1.6	1.6	1.1	15.6	1.3	11.1	8.7	4.7	3.9
Forest mixture type*		BeSp	BeSp	BeDgl	Be	BeSp	BeDgl	Be	BeSp	BeSp	BeDgl	BeDgl	BeAsMa	BeAsMa	BeAsMa
Harvested sample trees		5	5	10	15	5	5	10	5	5	5	5	5	5	5
Mean Hegyi-index**		0.75	0.90	0.97	1.81	1.19	1.65	0.93	1.10	1.61	1.32	2.34	0.79	0.95	0.71
Main tree species		Be	Be	Be	Be	Be	Dgl	Be	Be	Be	Dgl	Be	Be	Be	Be
Age [a]		88	88	79	72	72	53	93	90	85	62	90	111	93	73
Standing volume [m^3/ha]		229	186	168	215	215	316	375	172	316	188	337	361	300	159
Share [%]		65	53	48	83	83	78	100	50	85	45	85	84	70	45
Top height [m]		30.2	30.2	30.8	25.5	25.5	32.6	31.3	27.4	32.0	32.3	33.1	33.7	34.2	29.6
Mean DBH [cm]		31	31	29	22	22	38	33	28	31	39	34	39	36	26
Heavy crown thinning [m^3/ha]	2011	–	–	29.7	–	–	–	–	–	–	–	–	–	–	–
	2012	–	–	–	–	–	–	–	–	–	12.1	–	–	–	–
	2013	–	–	–	–	–	3.7	–	–	–	–	93.2	–	–	–
	2014	–	–	–	–	–	–	–	–	–	–	–	54.0	–	–
	2015	–	15.9	10.5	–	–	–	–	62.0	12.2	–	–	–	–	–
	2016	–	–	–	–	–	–	–	–	–	–	–		10.3	7.3

Note that pure beech stands were only located in the forest district Reinhausen. For further information on the forest stands the reader is referred to Höwler et al. (2017) and Höwler et al. (2019)

***Be**, pure beech; **BeAsMa**, beech mixed with ash and maple; **BeDgl**, beech mixed with Douglas-fir; **BeSp**, beech mixed with spruce ****Mean Hegyi-Index** (competition index calculated according to Hegyi (1974) cited in Bachmann (1998) for each sample tree including all competitors within a sample circle of 15 m radius) per all harvested sample trees per department

Table 2 Description of the investigated sample tree material from four *forest mixture types*: mixed European beech stands with Norway spruce, with ash and maple, with Douglas-fir, and pure European beech stands

Forest mixture type	Tree species	Age (min–max)	DBH [cm] (med. ± SD)	*n* trees	*n* log sections	*n* boards	*n* height strata (min–max)	*n* board groups (lower, upper)
Pure	*Fagus sylvatica* L	72–93	41.1 ± 4.4	25	50	574	14 (0–650 cm)	20, 15
Mixed	*Fagus sylvatica* L., *Picea abies* (L.) H. Karst	72–90	42.6 ± 6.1	25	50	552	20 (0–950 cm)	27, 23
Mixed	*Fagus sylvatica* L., *Pseudotsuga menziesii* (Mirb.) Franco	53–90	37.7 ± 6.9	25	50	499	20 (0–950 cm)	23, 13
Mixed	*Fagus sylvatica* L., *Acer platanoides* L./ *Acer pseudoplatanus* L./ *Fraxinus excelsior* L	73–111	51.2 ± 7.4	15	30	275	16 (0–750 cm)	14, 11

Listed are the main tree species, the minimum and maximum age as well as the median (med.) diameter at breast height (DBH) ± standard deviation (SD) of the sample European beech trees, the number (*n*) of sample trees, of log sections (LS), of analyzed boards, height strata (HS), and board groups (BG) for the lower and upper log sections

Fig. 1 Camera arrangement for the image acquisition at the Fehrensen GmbH showing the vertical distance to the board surface of 1 m and the angle to the board surface of 90° (created using INKSCAPE version 0.92 and Adobe Photoshop CS3 Extended version 10.0; source Höwler et al. 2019)

surface from bottom to top (Fig. 3). These merged log sections were then divided into small height strata of 50 cm length, beginning with the first height strata at 0–50 cm (stump excluded) and ending with the last and maximum height strata at 950–1000 cm. During the internal timber quality assessment using Datinf® Measure, the height above the forest floor was assigned to all measured attributes providing the beginning and end of a quality attribute along the vertical axis. As some measured quality attributes covered more than one height strata, we calculated the proportions of each measured *knot surface* within each height strata using the total length, the beginning and ending values, as well as the total surface of a quality attribute. The *knot surface* per height strata was then calculated using Eq. 1:

$$\text{knotsurface}_{0-50\text{cm}}[\%] = \left(\frac{\sum_{i=1}^{n} \text{knotsurfaces}_{i_{0-50\text{cm}}} \left[\text{cm}^2\right]}{\sum_{i=1}^{n} \text{boardsurfaces}_{i_{0-50\text{cm}}} \left[\text{cm}^2\right]} \right) * 100 \quad (1)$$

Since the log sections varied in length (due to the commercial sawing procedure), we used relative heights. For this purpose, the maximum length of the log sections per sample tree was determined (e.g., two log sections of 3 m, resulting in a maximum length of 6 m in total). This maximum length was set as 100%, the 50 cm height strata were adjusted accordingly.

Statistical analysis

All statistical analyses were performed using the free and open-source-software R (version 4.0.4, R Core Team 2018) with a significance level set at $p < 0.05$. The Shapiro–Wilk normality test was applied to test for normal distribution of the data.

Horizontal distribution of knot surface

The response variable *knot surface* was not normally distributed and we used arcsine transformation (y) for percentage

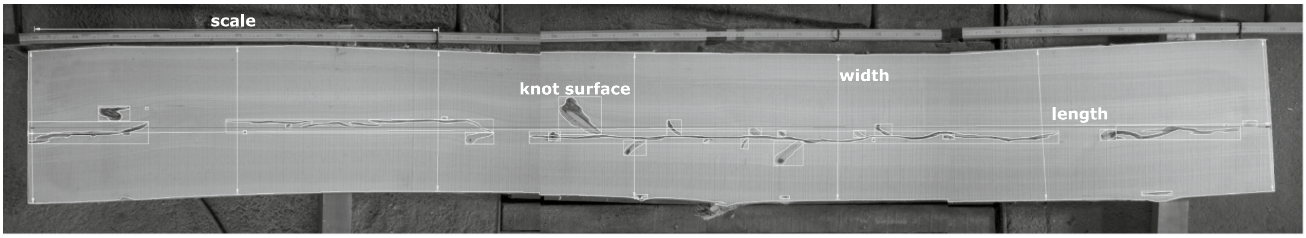

Fig. 2 Measurement of one board using the software Datinf® Measure including the total length, the widths assessed every 50 cm, knot surfaces, and the total board surface. The scale on the measuring tape equaled 100 cm and enabled a transformation from pixel into metric units (created using IrfanView version 4.42 and Inkscape version 0.92)

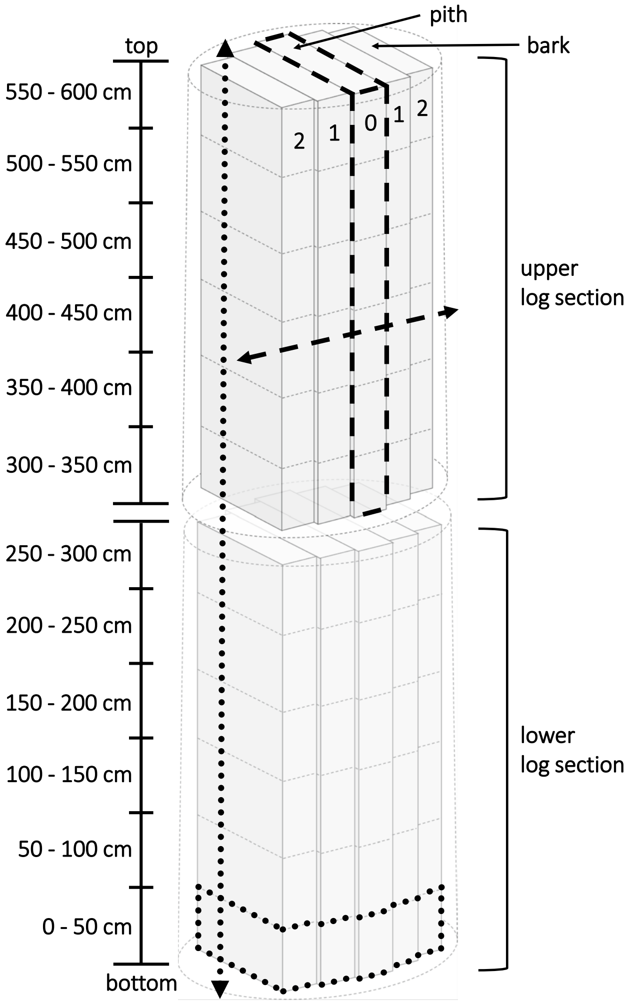

Fig. 3 Exemplary virtual composition of the boards of one European beech sample tree with two log sections of 3 m length each (lower log section: 0–300 cm, upper log section: 300–600 cm) and an unequal number of boards ($n = 5$). Shown are the central board (group 0, equals the central board) and two subsequent board groups (group 1 and group 2, according to the *distance from the central board*) for the horizontal distribution of the timber quality attribute *knot surface* (dashed) as well as the height strata of 50 cm (starting with the first strata at 0–50 cm, ending with the last strata at 550–600 cm) for the vertical distribution of the timber quality attribute *knot surface* (dotted)

data to linearize the relationship between the response and explanatory variables along the horizontal stem axis (Crawley 2012). The horizontal distribution of *knot surface* was analyzed for different *forest mixture types* using a linear mixed-effect model ('lmer' function of the package 'lme4'; Bates et al. 2015). In the linear mixed-effect model, '*distance to central board*,' '*forest mixture type*,' as well as interaction of '*distance to central board*' and '*forest mixture type*' were included as fixed effects. '*Tree ID*' was set as random effect to account for correlation of boards of the same tree. To obtain R^2 from the linear mixed-effect model, we calculated marginal and conditional R^2. Marginal $R^2_{(m)}$ explains the proportion of variance by fixed effects and conditional $R^2_{(c)}$ the proportion of variance by both fixed and random effects (Nakagawa and Schielzeth 2013). The lower and upper log sections were analyzed separately, because the lower log sections contained more boards than the upper sections due to the natural taper of the trees.

Vertical distribution of knot surface

Since the assumptions for normal distribution were violated, generalized linear models (GLMs) were used to analyze the relationship between *knot surface* and the *relative log height* for different *forest mixture types*. The family of error structure was set to 'gamma' with an identity link function, as the quality attribute *knot surface* only had positive values.

Results

Horizontal distribution of knot surface

The linear mixed-effect model revealed a significant relationship between the quality attribute *knot surface* and *distance to central board* for the lower ($p < 0.001$, $R^2_c = 0.55$; Table 3) and upper ($p < 0.001$, $R^2_c = 0.55$; Table 4) log sections. With increasing *distance to the central board* the *knot surface* decreased by 0.021% mm^{-1} for the lower (Table 3) and by 0.029% mm^{-1} for the upper log sections (Table 4).

Table 3 Results of the linear mixed-effect model for the lower log Sects. (3–5 m) with *knot surface* (arcsine transformed) as response variable and *distance to central board* (distance) as explanatory variable

Fixed effects	Estimates	SE	df	*t*-value	*p* value	$R^2_{(m)}$	$R^2_{(c)}$
Intercept (Beech)	3.769	0.286	148.855	13.189	< 0.001	0.28	0.55
Distance	−0.021	0.002	860.000	−9.529	< 0.001		
BeechDouglasfir	0.515	0.407	152.661	1.266	0.207		
BeechAshMaple	0.233	0.486	158.908	0.479	0.632		
BeechSpruce	1.310	0.403	147.181	3.251	0.001		
Distance: BeechDouglasfir	−0.005	0.005	863.444	−1.432	0.152		
Distance: BeechAshMaple	−0.001	0.004	862.210	−0.344	0.731		
Distance: BeechSpruce	−0.012	0.003	864.700	−3.994	< 0.001		

Given are the parameter estimates, standard error (SE), degrees of freedom (df), *t*-statistics (*t*-value), model significance (*p* value), marginal R^2 ($R^2_{(m)}$) and conditional R^2 ($R^2_{(c)}$)

Table 4 Results of the linear mixed-effect model for the upper log Sects. (6–10 m) with *knot surface* (arcsine transformed) as response variable and *distance to central board* (distance) as explanatory variable

Fixed effects	Estimates	SE	df	*t*-value	*p* value	$R^2_{(m)}$	$R^2_{(c)}$
Intercept (Beech)	5.035	0.550	67.277	9.168	< 0.001	0.20	0.55
Distance	−0.029	0.005	334.828	−5.713	< 0.001		
BeechDouglasfir	−0.260	0.752	68.657	−0.345	0.731		
BeechAshMaple	0.477	1.127	73.871	0.423	0.674		
BeechSpruce	1.477	0.757	65.789	1.950	0.055		
Distance: BeechDouglasfir	0.006	0.008	337.332	0.791	0.430		
Distance: BeechAshMaple	0.004	0.009	337.205	0.387	0.699		
Distance: BeechSpruce	−0.010	0.007	337.889	−1.536	0.125		

Given are the parameter estimates, standard error (SE), degrees of freedom (df), *t*-statistics (*t*-value), model significance (*p* value), marginal R^2 ($R^2_{(m)}$) and conditional R^2 ($R^2_{(c)}$)

This corresponds to a decrease of 2.1% per 10 cm DBH increment for the lower and 2.9% for the upper log sections, resulting in a 10% decrease of *knot surface* for logs with a DBH of approximately 60 cm. The proportion of variance explained by fixed effects (*distance to central board*, *forest mixture type*, interaction of *distance to central board* and *forest mixture type*) accounted for 28% for the lower and 20% for the upper log sections (Tables 3, 4).

Knot surface was larger for boards close to the pith and decreased towards the bark (Fig. 4a and b). Furthermore, larger *knot surfaces* were observed for the upper log sections compared to the lower log sections and the decrease of *knot surface* along the horizontal stem axis was more steeply for the upper compared to the lower log sections. Additionally, the upper log sections visually showed a more scattered *knot surface* along the horizontal stem axis (Fig. 4a and b).

For the lower log sections, *knot surface* was found to be differently distributed along the horizontal stem axis in dependence of the neighboring tree species. The internal boards (*distance to central board* = 0 mm) of beech sample trees surrounded by Norway spruce had larger *knot surfaces* on average, compared to beech sample trees from pure stands (intercept beech and spruce: 5.079% *knot surface*; pure beech intercept: 3.769% *knot surface*, Table 3). For beech sample trees in mixture with Douglas-fir as well as with ash and maple no significant relationship between the *knot surface* and *distance to the central board* was observed. The linear mixed-effect model was therefore reduced by merging ‘pure beech stand’ with the mixture types ‘beech with ash and maple’ as well as ‘beech with Douglas-fir.’ The merged group was tested against the mixture type ‘beech with spruce.’ We found that internal boards (*distance to central board* = 0 mm) of beech mixed with spruce had larger *knot surfaces* that decreased more steeply with increasing *distance to the central board* compared to the grouped forest mixture types (Fig. 5). For the upper log sections, there was no significant difference ($p < 0.05$) between the forest mixture types (Table 4).

Vertical distribution of knot surface

The GLM analysis revealed a significant positive relationship between *knot surface* and *relative log height* ($p < 0.001$, $R^2_{\text{pseudo}} = 0.043$) for European beech trees from pure beech stands, from mixed stands with Douglas-fir, or from mixed stands with Norway spruce (Table 5). With increasing *relative log height,* the quality attribute *knot surface* increased (0.004 ± 0.001% *knot surface*); however this relationship was very weak. At stem basis (0% *relative log height*, Fig. 6), beech trees from mixture with Norway

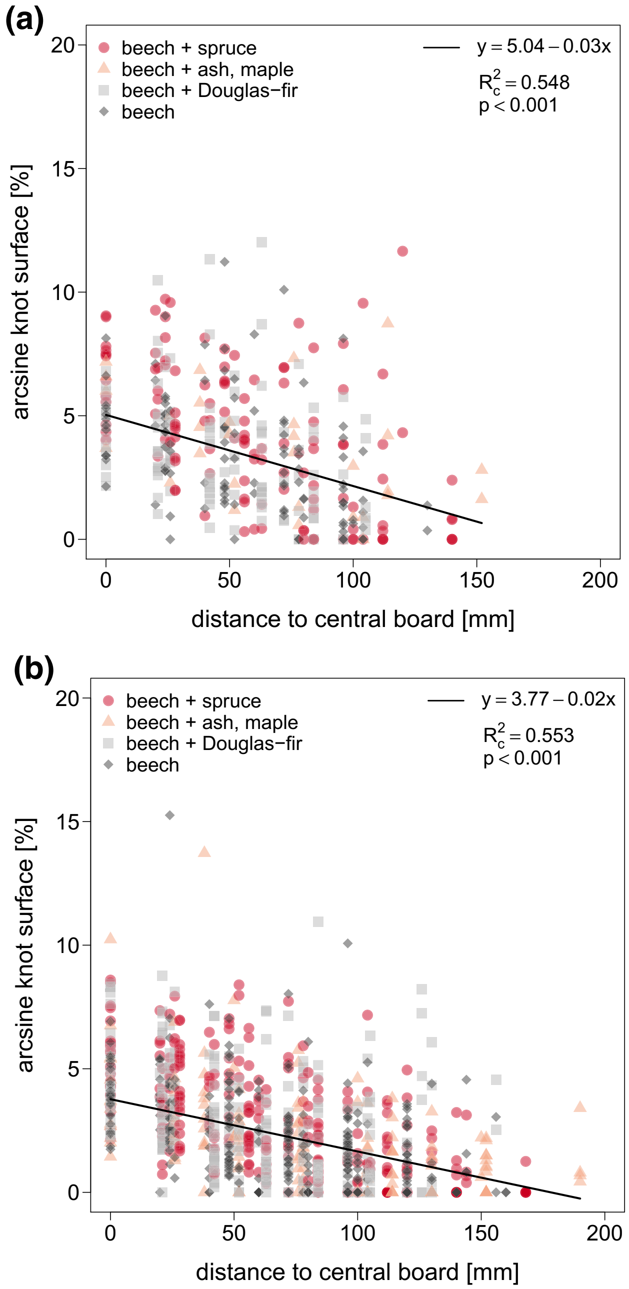

Fig. 4 Relationship between arcsine *knot surface* [%] and *distance to the central board* [mm] for **a** the lower log Sects. (3–5 m height) and **b** the upper log Sects. (6–10 m height) of European beech trees from mixed forest stands with Norway spruce, with ash and maple, with Douglas-fir, and from pure beech stands. The lines refer to the applied linear mixed-effects models. Significant relationships at $p < 0.05$ are presented

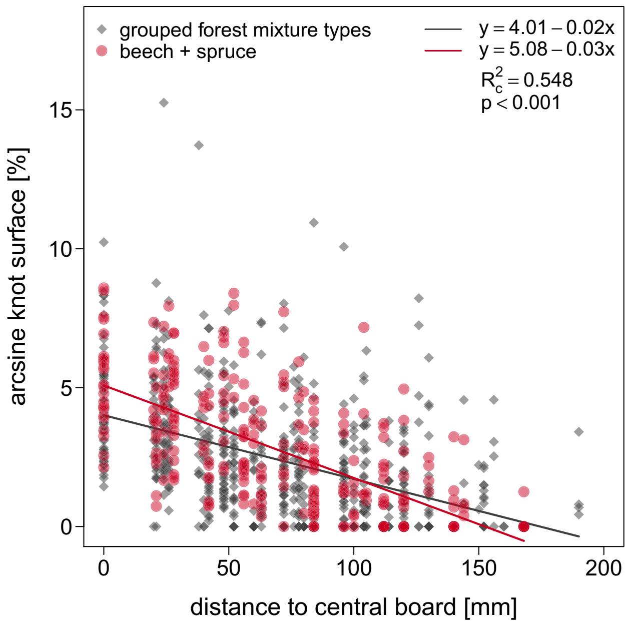

Fig. 5 Relationship between arcsine *knot surface* [%] and *distance to the central board* [mm] for the lower log Sects. (3–5 m height) of European beech trees from mixed forest stands with Norway spruce, with ash and maple, with Douglas-fir, and from pure beech stands. The forest mixture types 'pure beech,' 'beech mixed with ash and maple' as well as 'beech mixed with Douglas-fir' were merged and are displayed in gray rhomb. The lines refer to the applied reduced linear mixed-effects model. Significant relationships at $p < 0.05$ are presented

spruce had the largest *knot surfaces* (0.32 ± 0.043%), followed by beech trees from mixture with Douglas-fir (0.28 ± 0.041%). Smallest *knot surfaces* at 0% *relative log height* were found for European beech trees from pure beech stands (0.198 ± 0.03%). In a similar way to the distribution of *knot surface* along the horizontal stem axis, the *knot surface* along the vertical axis was at most 9%.

Over the entire *relative log height* (0–100%), beech trees from mixture with spruce showed the largest *knot surface*, followed by beech trees from mixture with Douglas-fir. Beech trees from pure stands showed the smallest *knot surface* (Fig. 6). When mixed with ash and maple the relationship was not significant. Expressed in absolute values, 100% *relative log height* (in relation to the maximum length of the analyzed tree) of the 90 European beech sample trees ranged from 6.14 m (average pure beech stands) to 6.96 m (average mixed stands with spruce).

Discussion

Question 1: How is the timber quality attribute *knot surface* distributed along the horizontal and vertical stem axis of European beech trees?

The lower log sections (up to approximately 10 m height) of deciduous trees are usually economically most valuable and can contain up to 80% of the timber value (Bachmann

Table 5 Results of the generalized linear model to describe the relationship between the response variable *knot surface* [%] dependent on the explanatory variables *relative log height* [%] as well as *forest mixture type*

Quality attribute	Model parameter	Estimate	SE	*t*-value	*p* value	R^2_{pseudo}
Knot surface	*Relative log height*	0.004	0.001	7.166	< 0.001	0.043
	Beech	0.198	0.030	6.679	< 0.001	
	Beech + Douglas-fir	0.082	0.041	2.020	0.044	
	Beech + ash, maple	− 0.059	0.037	− 1.625	0.104	
	Beech + spruce	0.126	0.043	2.945	0.003	

Given are the model parameter estimates (estimate) with their standard errors (SE), t-statistics (*t*-value), model significance (*p* value), and pseudo R squared (R^2_{pseudo})

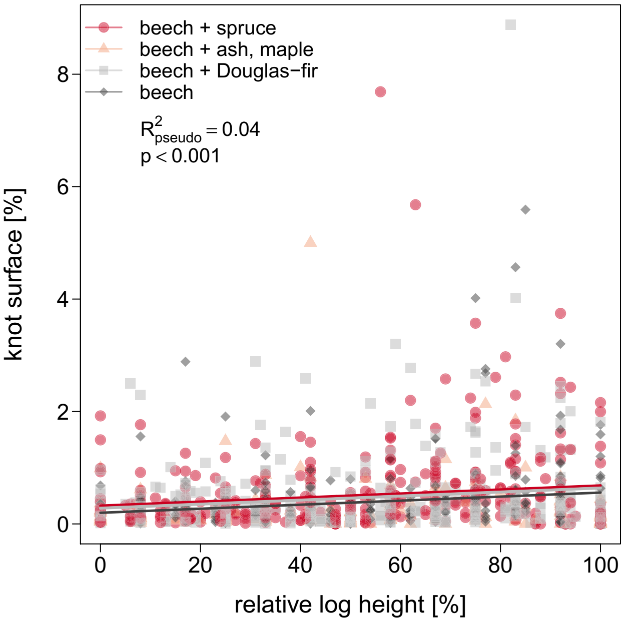

Fig. 6 Relationship between *relative log height* [%] and *knot surface* [%] of European beech trees from mixed forest stands with Norway spruce, with ash and maple, with Douglas-fir, and from pure beech stands. The lines refer to the applied generalized linear models with gamma family distribution. Only significant relationships at $p < 0.05$ are presented

1970; Kint et al. 2010). The timber value of a tree is related to the branch characteristics and the self-pruning of trees at younger ages (Kint et al. 2010). Thus, as the initial part of branches will be encased within the stem, the position and the extent of these branches are of great importance for timber quality (e.g., European standard EN 1316–1:2012; Deutsches Institut für Normung e. V. 2013). The most important silvicultural tool to influence branchiness in close-to-nature forestry is to control competition by managing stand density through thinning. Once the desired degree of self-pruning has been achieved, a phase of crown release is usually initiated in order to promote diameter growth of a now branch-free valuable lower stem (e.g., Hein 2008; Pretzsch 2019). The higher branchiness and branch dimensions on the upper log sections are tolerated, as high stem volume increment is intended. This practice was reflected in our study since the *knot surfaces* significantly increased with increasing *relative log height* (even though the relationship was rather weak). As the diameter increases, the proportion of branch-free wood on the log also increases outwardly in horizontal direction. This holds true for the investigated European beech trees studied here since *knot surface* significantly decreased along the horizontal stem axis with larger *knot surface* on boards close to the determined center of the logs. In summary, timber quality increased along the horizontal stem axis and decreased along the vertical stem axis with highest timber quality for the outer parts of the lower log sections of the investigated European beech trees. The results imply that the silvicultural treatments applied up to the day of harvest have effectively reduced knottiness in the lower and most important stem sections as well as in the outer boards of the logs. This supports hypothesis (i) stating that 'the timber quality attribute *knot surface* increases along the horizontal stem axis and decreases along the vertical stem axis as a result of the applied silvicultural treatment.' Obviously, the effect of a quite homogeneous silvicultural treatment (heavy thinning from above) in all kinds of investigated stands was stronger than the species identity effect. This view is supported by rather similar mean competition indices (cf. Table 1). Unfortunately, no information was available for the timber quality of European beech trees from unmanaged stands and thus stronger competitive pressure.

Question 2: How does neighborhood species identity affect the timber quality attribute *knot surface* of European beech trees?

We hypothesized higher timber quality of European beech trees from pure compared to mixed forest stands due to the higher intraspecific competitive pressure of European beech (Dieler 2011; Metz et al. 2013; Bauhus et al. 2017b). High intraspecific competitive pressure should lead to higher self-pruning and reduced knottiness. Since we observed higher timber quality in terms of smaller *knot surface* in pure beech stands compared to mixed beech stands with Norway spruce, our results support hypothesis (ii) that the timber quality attribute *knot surface* is smaller in pure compared to mixed beech stands due to higher intraspecific competition. This finding is in accordance with, e.g., Pretzsch and Rais (2016) who reviewed more than 100 publications on the morphology of mixed versus pure forest stands and deduced decreased timber quality in mixed forest stands (due to more heterogeneous growing conditions) from these publications. Their review focused on wood properties relevant for construction wood (e.g., knots, density). In our study, the smallest values for *knot surface* were found in sample trees from pure beech forest stands and largest in mixture with Norway spruce. This result might be attributable to a complementary light ecology of European beech and Norway spruce. Spruce crowns are cone-shaped, comparably narrow and triangular, whereas beech crowns are a cubical paraboloid (Pretzsch 2019). In mixture with Norway spruce, beech shows a greater horizontal and vertical crown expansion (Pretzsch and Rais 2016; Barbeito et al. 2017), which can result in vertically layered canopies (Pretzsch 2014) as well as in a shift of the crown towards a deeper stem section (Pretzsch and Rais 2016; Barbeito et al. 2017). The reason for this is seen in a more heterogeneous horizontal and vertical structure, which allows more light to reach lower canopy layers in mixed forest stands leading to delayed crown-uplifting (Pretzsch and Rais 2016), consequently leading to a delay in self-pruning compared to pure beech stands (cf. Bayer et al. 2013) and a higher *knot surface*. In contrast to mixtures with Norway spruce, no significant effect of neighborhood species identity was observed for beech trees mixed with Douglas-fir (along the horizontal stem axis and a rather weak relationship was found along the vertical stem axis). Initially, we had expected similar effects of the two conifers on beech timber quality. However, it may be that Douglas-fir, a species with higher growth rates than Norway spruce, have exerted stronger competition to beech than Norway spruce (Schütz and Pommerening 2013). Thus, we assume that Douglas-fir, which has found to be able to even outcompete beech (Bartelink 2000), resembled more the intraspecific competition of beech than the interspecific interference by spruce. In pure forest stands, trees occupy the same ecological niche with high intraspecific competitive pressure, whereas in mixed forest stands complementary effects can be observed resulting in reduced competition (Ammer 2017; 2019). Beech exposes highest intraspecific competition (Dieler 2011; Metz et al. 2013) and sample trees might thus have benefited from the lowered competition in mixture with spruce and expanded their crowns, which led to higher branch diameters and correspondingly higher knottiness. This could explain the observed larger *knot surface* (less natural pruning) in mixed forest stands with Norway spruce. Not only the total *knot surface* was larger in mixture with spruce, but also the central boards were knottier. This is due to less intense competition even from a young stand age and a lower stand density in coniferous-deciduous mixtures (compared to monospecific stands) caused by ecological niche complementarity. This is consistent with the fact that the smallest values of *knot surface* along the vertical stem axis were observed in pure beech stands and the largest values in mixture with Norway spruce. Neighborhood density and thus competition intensity seemed to be very important for controlling timber properties and might outweigh possible mixing effects.

A methodological shortcoming of our study was that the investigated forest stands are commercially managed and have undergone a history of thinning measures. The majority of the sample trees was classified as quality grade B or C (good and medium quality according to German quality grading guidelines, RVR 2014) and none of the investigated sample trees were classified in grade A (best quality) or grade D (bad quality). Nevertheless, an earlier study could show that this visual external quality grading (RVR 2014) of the sample trees conducted by local foresters was in compliance with internal timber quality attributes (Höwler et al. 2019). For these reasons, we support hypothesis (ii) that timber quality (in terms of *knot surface*) is higher in pure beech stands compared to mixed beech stands with conifer tree species such as Norway spruce. Since the proportion of beech trees within the mixed forest stands was also rather high, we cannot exclude intraspecific competition to a certain degree even there. This indicates that the observed (small) differences between pure and mixed forest stands might be even more pronounced in solely interspecific neighborhoods (cf. share of main tree species in Table 1) and highlights the importance of continuing to study the effect of neighborhood species identity on timber quality in mixed forest stands.

Conclusion

Even though comparatively good timber quality grades and a consistently rather small *knot surface* were found for European beech trees in mixed stands, we were able to detect significant differences between the stand types—even though they were small. The results showed that for European beech the *knot surface* on the horizontal and vertical stem axis appears to be affected differently depending on the neighboring species, which implicitly means that it can be controlled through silvicultural measures. Thus, although mixed forest stands are advantageous in several respects, the possibility of lower timber qualities (for European beech) should be taken into account for future forestry scenarios calculating with lager proportions of mixed stands. However, we only investigated the timber quality of European beech and have no information on the qualities of the admixed tree species that might compensate a 'quality loss' of beech timber. Moreover, for the investigated European beech trees, the differences between the stand types were small, did not change the timber value and are of low impact for the timber industry due to the small values for *knot surface*. Against this background, there is little to be said against but much to be said in favor of managing beech in mixed stands, since the actual outcome of timber quality seems to depend not only on the admixed tree species, but on stand management regime and hence forest structure, which was however not investigated here. Adequate silvicultural treatments in terms of stand density, competition control, tree species selection and distribution within forest stands could support the achievement of high-quality deciduous timber with reduced branchiness and knottiness even in mixed forest stands. To use the positive effects of intraspecific competition on beech timber quality on the one hand but promote mixed stands on the other hand, group-wise mixtures of tree species seem to be a promising concept. However, for features more dependent on the complementarity effect, single-species mixtures might still be the method of choice, highlighting that prioritization of management goals is essential for effective multifunctional silviculture.

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Declarations

Conflict of interest None declared.

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