Influence of intra- and interspecific competition on timber quality of European beech

Dissertation

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„Nicht alles, was vom Normalen abweicht, ist auch fehlerhaft.“
Christoph Richter

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3D	Three-dimensional
AICc	Akaike's information criterion corrected for small sample sizes
BA	Bark anomalies
BSA	Board surface area
CI	Competition index
CLT	Cross laminated timber
DBH	Diameter at breast height
Dist	Distance
DPI	Dots per inch
Eq	Equation
FAO	Food and Agriculture Organization of the United Nations
GAM	Generalized additive model
GLM	Generalized linear model
Glulam	Glued laminated timber
GOF	Goodness of fit
H	Height
H/D	Height to diameter
I	Target/Sample tree
J	Competitor tree
L	Lean
LVL	Laminated veneer lumber
MBB	Mixed beech stands with other broadleaved tree species
MBD	Mixed beech stands with Douglas-fir
MBN	Mixed beech stands with Norway spruce
MCS	Mean discoloration surface
MKS	Mean knot surface
NLS	Non-linear least square
OB	Other broadleaved tree species
PB	Pure beech stands
QCB	Quality class B
QCC	Quality class C
S	Sweep
SD	Standard deviation
SNC	Stem non-circularity
TLS	Terrestrial laser scanning

Summary

The timber quality of a single tree is considerably influenced by interactions with other individual trees. These competitive effects from neighbouring trees may be regulated through silvicultural treatments. Consequently, the competition a tree faces until the day of harvest is a strong driver for timber quality. This turns the regulation of competition into an integral part of silviculture. However, not only competition intensity determines quality. The species identity of neighbouring trees and forest mixture type can also influence quality related stem attributes such as branchiness or tree shape. Against the background of a forest management that is close to nature and adapted to climate change, the share of mixed forests and of deciduous trees has increased in the recent past and will continue to increase in the future. Therefore, it becomes important to understand the effects of different tree species mixtures and interactions on the quality of trees. Although mixed forest stands have been extensively investigated, research mostly focused on tree growth and productivity, or resistance and resilience under changing and uncertain climate conditions, but rather less on the effects of tree species mixing on timber quality. It is still unclear whether the numerous positive effects of mixed forests come at the expense of timber quality. Currently, pure coniferous forests are converted into mixed and deciduous forests and this will eventually lead to a changed availability of hardwood and softwood. Thus, deciduous timber will have to be used more intensely in the future. However, for that, information on deciduous timber quality in mixed forest stands is needed.

In-situ measurements of timber quality have the potential to improve the economic yield of a stand, the sustainable utilisation of timber and timber products, and can further contribute to an optimal harvesting time. However, precise information on timber quality of deciduous trees, especially of standing trees, has often been lacking so far. In addition, measurements of quality attributes or the competitive situations of a tree have so far required high measuring efforts that were affected by significant errors in higher log sections. Through terrestrial laser scanning (TLS) it became possible to obtain a virtual three-dimensional (3D) representation of a tree and its direct neighbours. This enables a quantitative assessment of quality-related external stem characteristics of a tree in dependence of its neighbourhood. This thesis therefore aims to provide a quantification of both external and internal timber quality characteristics (e.g., bumps, branches, knots, discoloration) in order to investigate to what extent intra- and interspecific competitive situations affect these quality characteristics of European beech (*Fagus sylvatica* L.).

Three different approaches were applied to analyse the effects of competition intensity and tree species identity of neighbouring trees on timber quality of 125 target European beech trees: TLS, a quality assessment on the standing tree by the local district foresters, and a quality assessment of the sawn timber (boards) after harvesting. In addition, the suitability of TLS for a quantitative assessment of external quality characteristics was examined. The relationship between external and internal quality characteristics was investigated by comparing the different approaches of quality assessment. Photographs of the sawn boards were used for a quantitative measurement of discolouration surface and knot surface as indicators of timber quality using the software Datinf® Measure.

The external stem quality of European beech was significantly influenced by the degree of competition intensity. More precisely, two TLS-based measures of external stem quality that were newly developed in this work were influenced by the intensity of competition: With increasing competition intensity, the number of bark anomalies (BA) and stem non-circularity (SNC) decreased. Hence, external stem quality of European beech can be measured non-destructively, objectively, and quantitatively applying TLS. This makes TLS a valuable addition to a visual *in-situ* timber quality assessment. Furthermore, the externally visible quality features measured using TLS correlated to the internal timber quality. Similarly, the quality assessment of the local district foresters also correlated with the internal timber quality. Thus, external quality features help to predict the internal timber quality. This was exemplified, among other things, by the fact that it is possible to predict discoloration by the number of bark anomalies on the stem surface. Internal timber quality was also related to the competitive situation, with increasing competition improving internal timber quality. In pure beech stands, a tendency towards better quality with lower knot surfaces was observed compared to mixed stands of beech and spruce (*Picea abies* (L.) H. Karst.). In addition, a decrease in knot surface was found with increasing distance to the pith and lower values in the lower stem sections.

These results suggest that the regulation of competitive levels through silvicultural treatments can improve timber quality and thus confirm empirical findings that indicate a positive relationship between competition intensity and timber quality. Although single effects of neighbourhood species identity could be identified, the overall species effect on timber quality was lower than the competitive effect resulting from size and distance of neighbouring trees. Lastly, this study provides a new methodology to assess external timber quality measures in the field objectively and non-destructively.

Zusammenfassung

Die Holzqualität jedes Baumes wird durch die Wechselwirkungen mit anderen Bäumen erheblich beeinflusst. Diese Konkurrenzeffekte durch benachbarte Bäume können durch waldbauliche Maßnahmen reguliert werden. Folglich ist die Intensität der Konkurrenz, der ein Baum bis zum Tag der Ernte ausgesetzt ist, ein bedeutender Treiber für die Holzqualität. Dadurch wird die Regulierung der Konkurrenz zu einem wesentlichen Bestandteil des Waldbaus. Doch nicht nur die Konkurrenzintensität bestimmt die Qualität. Auch die Artidentität benachbarter Bäume und Mischungen von Baumarten können qualitätsrelevante Stammmerkmale wie z.B. die Astigkeit oder die Stammform beeinflussen. Vor dem Hintergrund einer naturnahen und an den Klimawandel angepassten Waldbewirtschaftung hat der Anteil der Mischwälder und der Laubbäume in der jüngsten Vergangenheit zugenommen und wird auch in Zukunft weiter zunehmen. Daher wird es wichtig, die Auswirkungen verschiedener Baumartenmischungen und Wechselwirkungen auf die Qualität der Bäume zu verstehen. Obwohl Mischwaldbestände umfassend untersucht wurden, konzentrierte sich die Forschung hauptsächlich auf das Wachstum und die Produktivität der Bäume oder die Widerstandsfähigkeit unter wechselnden und unsicheren Klimabedingungen, aber weniger auf die Auswirkungen der Baumartenmischung auf die Holzqualität. Insbesondere ist noch unklar, ob die zahlreichen positiven Auswirkungen von Mischwäldern mit einer Verschlechterung der Holzqualität einhergehen. Gegenwärtig werden reine Nadelwälder in Misch- und Laubwälder umgewandelt, und dies wird langfristig zu einer veränderten Verfügbarkeit von Laub- und Nadelholzanteilen führen. Daher wird Laubholz in Zukunft intensiver genutzt werden müssen. Dazu werden jedoch Informationen über die Laubholzqualität in Mischwaldbeständen benötigt.

In-situ-Messungen der Holzqualität haben das Potenzial, den wirtschaftlichen Ertrag eines Bestandes und die nachhaltige Nutzung von Holz und Holzprodukten zu verbessern und können darüber hinaus zur Optimierung des Einschlagszeitpunktes beitragen. Bislang fehlen jedoch oft genaue Informationen über die Holzqualität von Laubbäumen, insbesondere von stehenden Bäumen. Zudem erforderte die Messung von Qualitätsmerkmalen oder der Konkurrenzsituation eines Baumes bisher einen hohen Messaufwand, der in höheren Stammabschnitten zudem durch erhebliche Fehler beeinträchtigt war. Durch terrestrisches Laserscanning (TLS) wurde es möglich, ein virtuelles dreidimensionales Modell eines Baumes und seiner direkten Nachbarn zu erhalten. Dies wiederum eröffnet die Möglichkeit, qualitätsrelevante äußerer Stammeigenschaften eines einzelnen Baumes in Abhängigkeit von seiner Nachbarschaft quantitativ zu erfassen und zu beurteilen. Ziel dieser Arbeit war es daher, sowohl äußere als auch innere Holzqualitätsmerkmale quantitativ zu erfassen, um zu untersuchen, inwieweit sich intra- und interspezifische Konkurrenzsituationen auf diese Qualitätsmerkmale der Buche (*Fagus sylvatica* L.) auswirken.

Zur Analyse der Auswirkungen von Konkurrenzintensität und Artidentität der Nachbarbäume auf die Holzqualität von 125 Untersuchungsbäumen der europäischen Buche wurden drei verschiedene Ansätze angewandt: TLS, eine Qualitätsbeurteilung am stehenden Stamm durch die örtlichen Revierförster und eine Qualitätsbeurteilung des Schnittholzes (Bretter) nach dem Einschlag. Darüber hinaus wurde die Eignung von TLS für eine quantitative Bewertung der äußeren Qualitätsmerkmale untersucht. Der Zusammenhang zwischen äußeren und inneren Qualitätsmerkmalen wurde über den Vergleich der verschiedenen Ansätze zur Qualitätsbeurteilung untersucht. Fotos der gesägten Bretter wurden für eine quantitative Messung der Astfläche und der Verfärbungsfläche als Indikatoren für die Holzqualität mit der Software Datinf® Measure verwendet.

Die äußere Stammqualität der europäischen Buche wurde wesentlich durch den Grad der Konkurrenzintensität beeinflusst. So wurden zwei im Rahmen dieser Arbeit neu entwickelte TLS-basierte Maße der äußeren Stammqualität durch die Konkurrenzintensität beeinflusst: Mit zunehmender Konkurrenzintensität nahmen die Anzahl der Rindenanomalien pro Meter und die Stammunrundheit ab. Somit können Merkmale der äußeren Stammqualität der europäischen Buche zerstörungsfrei, objektiv und quantitativ mit TLS gemessen werden. Damit stellt TLS eine wertvolle Ergänzung zu einer *in-situ* Erfassung der Holzqualität dar. Darüber hinaus korrelierten die mit TLS gemessenen äußerlich sichtbaren Qualitätsmerkmale mit der inneren Holzqualität. Gleichermaßen korrelierte auch die Qualitätsbeurteilung der lokalen Revierförster mit der inneren Holzqualität. Somit ermöglichen äußere Qualitätsmerkmale eine Vorhersage der inneren Holzqualität. Dies wurde unter anderem durch die Möglichkeit der Vorhersage von Verfärbungen durch die Anzahl von Rindenanomalien auf der Stammoberfläche verdeutlicht. Auch die innere Holzqualität stand im Zusammenhang mit der Konkurrenzsituation, wobei ein zunehmender Konkurrenzdruck zu einer besseren inneren Holzqualität führte. In Buchenreinbeständen wurde im Vergleich zu Mischbeständen aus Buche mit Fichte (*Picea abies* (L.) H. Karst.) eine tendenziell bessere Holzqualität mit kleineren Astflächen gemessen. Zusätzlich nahm die Astfläche mit zunehmendem Abstand zur Markröhre ab und in den unteren Stammabschnitten wurden kleine Werte ermittelt.

Diese Ergebnisse deuten darauf hin, dass eine Regulierung des Konkurrenzdrucks durch waldbauliche Maßnahmen zu einer Verbesserung der Holzqualität führen kann und bestätigen empirische Befunde, die auf einen positiven Zusammenhang zwischen Konkurrenzintensität und Holzqualität hinweisen. Obwohl einzelne Effekte verschiedener Nachbarschaft-

Artidentitäten identifiziert werden konnten, war dieser Effekt insgesamt geringer als der Konkurrenzeffekt, der sich aus Größe und Abstand benachbarter Bäume ergibt. Schließlich bietet diese Studie eine neue Methodik zur objektiven und zerstörungsfreien Erfassung und Bewertung der äußeren Stammqualität.

Chapter 1

General introduction

1. General introduction

1.1. Scientific motivation

The consequences of ongoing climate change are being observed worldwide. The mean surface temperature is rising, precipitation conditions are changing, and extreme weather events are becoming more frequent (IPCC 2019). Thus, droughts, heat waves and fires, storms, severe rainfall, and insect calamities have recently become more common and intense. These changes have a significant impact on forests and their growing conditions (Lindner et al. 2010) and lately damaged millions of trees in German forests. According to the German Federal Statistical Information Service (Statistisches Bundesamt 2019), the amount of harvested timber damaged by wind, storm, or insects in Germany reached about 32 million m³ in 2018. About 76 % of this was accounted for by Norway spruce (*Picea abies* (L.) H. Karst.). This high amount of damaged and finally unplanned harvested Norway spruce trees (Faltl et al. 2017) in German forests is a consequence of severe storm events (e.g., "Burglind" and "Friederike" in January 2018), followed by bark beetle infestation (Griess and Knoke 2011), which benefited from a weakened defence mechanism caused by extreme drought in 2018. Although Norway spruce is susceptible to storm damage due to its shallow root system, as well as being at high risk to insect calamities in times of drought (von Lüpke et al. 2004; Knoke et al. 2008), spruce has been planted extensively from the 18th century on far beyond its natural limits (Spiecker 2000; Spiecker 2003; Zerbe 2002). The reason for this lies in large-scale devastation and overexploitation of European forests and an associated shortage of wood supply (Zerbe and Wiegleb 2009). Woodland that was naturally dominated by broadleaved tree species was consequently reforested with coniferous monocultures, consisting primarily of Scots pine (*Pinus sylvestris* L.) or Norway spruce. These species were assumed to grow rapidly, being comparable easy to establish and to manage, and also offering favourable timber characteristics (Spiecker 2003; Zerbe and Wiegleb 2009). However, these pure coniferous forests are, as noted earlier, very susceptible to natural hazards. Yet the failing of a huge number of single species stands, a high degree of instability in a changing climate, and a loss of biodiversity have led to a reconsideration of mixed forests and to changes in forest policies in recent decades (Pretzsch et al. 2013).

Not only in Germany, but also in numerous countries around the world, forest management is being adapted to climate change by converting pure coniferous but also pure deciduous forests into mixed and site-appropriate forest stands (von Lüpke et al. 2004; Forest Europe 2015). Unlike the past forest generation, the next forest generation will consist largely of deciduous tree species (DHWR 2016) as the proportion of mixed forests and thus of broadleaved tree species has increased and will continue to increase in the future (BMEL 2018; Forest Europe

2015; DHWR 2016). The ratio between available hardwood to softwood will change considerably and the supply of hardwood on the timber market is already steadily growing since the new hardwood stands have reached sizes sufficient for sawing in the meantime (Dill-Langer and Aicher 2014; Weidenhiller et al. 2019). Especially the available beech timber volume will increase in the future (Dill-Langer and Aicher 2014) because for central Europe, European beech (*Fagus sylvatica* L.) has so far been of major importance for the conversion of pure to mixed forest stands due to its favourable ecological and regeneration properties (Ammer et al. 2008; Rumpf and Petersen 2008). Furthermore, beech is highly competitive and naturally dominates wide areas throughout Europe due to its large site amplitude (Leuschner 1998; Leuschner et al. 2006; Ellenberg and Leuschner 2010). Also, European beech is one of the most important deciduous tree species in Germany and is in demand by e.g., the German veneer industry (Hapla and Militz 2008). Beech also has better strength parameters compared to Norway spruce (Ammann and Niemz 2014). Despite its great potential, only high-quality logs are processed for sawn timber production and a high proportion of the annual beech wood harvest is used for pulp, paper, or energetic purposes (Hapla et al. 2002; Breinig et al. 2015). Meanwhile, glued laminated timber (glulam), laminated veneer lumber (LVL) as well as cross laminated timber (CLT) products have become a promising technology for the establishment of a wider range of hardwood products, also using medium- and lower-quality logs (Breinig et al. 2015; Weidenhiller et al. 2019). This in turn can be favourable for long-term carbon sequestrations in buildings (Breinig et al. 2015). Nonetheless, the establishment of new industrial applications and technologies for the processing and thus the usability of hardwoods of different qualities into different products is still necessary to solve the emerging conflict between the consistently high demand of softwood and the diminishing supply of softwood in the future. The problem of processing low-quality European beech wood is not completely solved yet and it is neither ecologically nor economically sustainable to use a high proportion of beech wood for energetic purposes only (Dill-Langer and Aicher 2014). Therefore, timber quality and an appropriate timber utilisation of different assortments of European beech are gaining importance in the coming decades (Hapla and Militz 2008; Pretzsch et al. 2018; Aicher et al. 2016; Pretzsch et al. 2018). Indeed, in view of the ongoing conversion of forests, it remains unclear what timber qualities and what assortments may be achieved in mixed forests.

Mixed forest stands are supposed to be advantageous compared to pure forest stands in several ways. Many of these advantages can be attributed to complementary effects, such as different crown and root shapes, spatial or temporal variations in resource use, or a redistribution of resources (Pretzsch et al. 2017). These complementary niche occupations could in turn e.g., enhance productivity. According to e.g., Pretzsch et al. (2015), standing volume, stand density, basal area growth, as well as stand volume growth were higher in mixed compared to pure stands. However, not only productivity may be influenced. Also the ecological stability of forests should, according to e.g., Knoke et al. (2008), be improved in mixed compared to pure forest stands after the establishment of deciduous trees to coniferous stands and vice versa. Trees that are highly susceptible to e.g., wind damage or insect calamities may benefit from the admixing with more resistant tree species, increasing the ecological stability of mixed forests (Knoke et al. 2008). In this way, if damage occurs in mixed forest stands, it becomes possible to react to low timber prices or fluctuations on the timber market and also maintain economic stability – provided that only one tree species is affected by damage while the other one remains economically stable (Knoke 2017). Additionally, biological diversity is supposed to be higher in mixed forest stands, since more habitats and ecological niches are provided (Ammer et al. 2008). However, the effects of mixed forests on biodiversity are dependent on the investigated variables and dimensions. Moreover, according to studies of Ehbrecht et al. (2017) and Juchheim et al. (2019), mixed forest stands can promote structural diversity, whereby structural diversity can be attributed to e.g., different canopy or vegetation covers, varying tree heights and tree diameters, tree spacing, the standing biomass, or deadwood (McElhinny et al. 2005). These are only several of the advantages of mixed forest stands over pure stands and illustrate that mixed forest stands have been investigated comparatively to pure stands in many ways. However, there is one aspect that has rarely been investigated so far but is of great economic importance: the influence of different forest mixtures on timber quality (Pretzsch and Rais 2016; Bauhus et al. 2017).

There is still only limited knowledge on how different species combinations affect the quality of trees and if the numerous advantages of mixed forest stands come at the expense of timber quality. Due to differing growth dynamics and differing ecological requirements of the mixed tree species, mixed forest stands are characterised by very uneven growth conditions (Pretzsch and Rais 2016). This may lead to a higher variability in stem and crown properties (Benneter et al. 2018) and potentially decreased timber quality. For example, Bayer et al. (2013) showed that the number of branches significantly increased in mixed compared to pure beech stands, which can be attributed to different light transmissions of different species in mixed forest stands (Pretzsch and Rais 2016). Also, Pretzsch and Rais (2016) have shown that the height to diameter (h/d) ratio can either increase or decrease in mixed forest stands as it is dependent on the mixture of species and their competitive ability. This is in compliance with Benneter et al. (2018) who stated that it depends on ecological properties such as crown plasticity, shade tolerance, or the competitive ability of the tree species whether a mixed forest stand will have a positive or negative effect on the stem quality. The effect of intra- and interspecific competition on timber quality gains importance and needs to be investigated. Yet the following question arises: How can timber quality be defined?

1.2. The concept of quality

The term 'quality' is used in everyday speech (Barfield 1967) and is commonly associated with adjectives such as poor, good, or excellent. Etymologically, 'quality' can be traced back to the Latin word *qualita*, which means goodness or constitution (Kluge and Seebold 1989, translated by author, p. 573). Numerous disciplines (e.g., economics, healthcare, sociology) use the term 'quality' with emphasis on very different aspects (Kathawala 1989). Therefore, various definitions exist. Attempts to generate a universally valid definition date back to the Greek philosophers Aristotle, Plato, or Socrates, who equated quality with *aretê*, meaning excellence (Reeves and Bednar 1994). According to Bielert (1997), there are historically a technological and an economically oriented definition of the term 'quality'. Representatives of the technically oriented direction understand 'quality' as the conformance of a product to a design, to specifications, or the compliance to requirements (e.g., Gilmore 1974 as cited in Reeves and Bednar 1994; Crosby 1980). In contrast, the economically oriented way of defining quality is determined by the customer's assessment of the conformity to own requirements, the capacity to satisfy wants, or the fitness for use (e.g., Feigenbaum 1988; Edwards 1974 as cited in Bielert 1997; Juran 1962; Juran et al. 1974).

Today, the term 'quality' is used in connection to the constitution of a certain product or service (Barrantes 2008). In this regard, quality often means good workmanship, functional performance, durability, or use of high-class materials (Bielert 1997). However, companies, customers, countries, or the field of application kept on interpreting the concept of 'quality' differently. Therefore, in 1972 an international valid definition was established, standardized and updated in 2015 (quality standard DIN EN ISO 9000:2015-11) which defines quality as the "degree to which a set of inherent characteristics[1] of an object[2] fulfils requirements[3]" (Deutsches Institut für Normung e. V. 2015). This implicates that quality can or must be measured with the aid of previously defined quality features for certain requirements. These requirements are, on the one hand, the technical specifications and, on the other hand, the customer requirements, which go beyond technical considerations (Barrantes 2008). Regardless of past or present, a

[1] "distinguishing feature" Deutsches Institut für Normung e. V. (2015).
[2] "entity, item, anything perceivable or conceivable" Deutsches Institut für Normung e. V. (2015).
[3] "need or expectation that is stated, generally implied or obligatory" Deutsches Institut für Normung e. V. (2015).

major commonality among the quality definitions is the focus on customer satisfaction (Wicks and Roethlein 2009). Thus, quality strongly depends on the end use and subjective preferences.

The same applies to timber quality: timber quality depends on a wide range of internal and external properties (e.g., tree shape, branches, density, or fibre length) and how these properties affect the intended use or the end product (Gartner 2005; van Leeuwen et al. 2011). This in turn depends on the customer, since different customers would rate the same quality differently based on their own requirements (Knoke et al. 2006). Various properties of wood, such as shape, colour, or knots can be assessed positively by ecologist or aesthetes, while the wood processing industry might relate these properties with higher efforts, inputs, and difficulties (Richter 2019). In order to define and classify timber quality, the forestry and timber sector in Germany established a uniform set of rules under private law including amongst others the quality grading of raw timber ("Rahmenvereinbarung für den Rohholzhandel in Deutschland (RVR)"). This voluntary agreement regulates e.g., the classification into quality grades for different tree species groups (spruce/ fir, pine, Douglas-fir/ larch, oak, and beech) based on previously defined quality measures. The quality grades range from A (best quality) to D (worst quality) and are listed in Table 1.1 following RVR (2014).

Table 1.1 Description of the quality grades A, B, C, and D according to "Rahmenvereinbarung für den Rohholzhandel in Deutschland" (RVR 2014).

Quality grade	Description
A	Logs of excellent quality, free of defects or only insignificant quality-reducing characteristics that hardly affect its use.
B	Logs of normal quality with few and/or moderately pronounced quality-reducing characteristics.
C	Logs of normal quality with increased and/or stronger distinctive quality-reducing characteristics.
D	Logs, which do not belong to classes A, B, C, because of their quality-reducing characteristics but can be used as logs.

For European beech, together with hornbeam in the tree species group "beech", the defined quality measures are knots (occluded, healthy, rotten), spiral grain, crookedness, cracks, injuries by insects, white rot, red heartwood, logging injuries, or bark damages (RVR 2014). Here, the amount, condition, and size of knots and thus the portion of tight and loose knots are an important quality feature because a single knot can downgrade an entire log (Hein 2008; Deutsches Institut für Normung e. V. 2013; RVR 2014; Stängle et al. 2014). For example, in quality grade A only one occluded knot every three meter with a ratio of branch scar height to branch scar width of less than 1:4 is admissible while in quality grade D also rotten knots are permitted (RVR 2014). This is due to the effects of knots on mechanical, physical but also aesthetic properties of wood (Torkaman et al. 2018). For example, the strength and stiffness but also swelling and shrinking behaviour of timber may change because of the presence of knots (Osborne and Maguire 2016; Richter 2019). Branch development and pruning determine the amount and size of knots and thus the knotty core, which is important for wood quality (Hein 2008). Furthermore, Knoke et al. (2006) found discoloration in high-quality beech timber to be the most important quality-grading criterion (mainly for aesthetic reasons).

In general, the quality of trees in managed forest stands depends on their genetic predisposition on the one hand, and on the other hand on site conditions, neighbourhood relations, and thus past growing conditions (Tomé and Burkhart 1989; Zingg and Ramp 2003; Richter 2019). The influence of neighbouring trees on a target tree and hence the exposed competition intensity is related to their size in comparison to the size of the target tree: a large neighbour is assumed to reduce the growth potential, while a smaller neighbour can be beneficial for the growth and the quality of the subject tree (Tomé and Burkhart 1989). This influence of neighbourhood relations on tree growth and timber quality is of special importance, since it can be cost-efficiently influenced by silvicultural interventions (Ammer 2008). For example, the regulation of stand density by varying planting densities and thinning units is a major silvicultural tool to adjust tree growth (Mäkinen and Hein 2006) and consequently promote timber quality. The quality of a log can substantially be improved by controlling the amount and the size of the living and dead branches, the portion of tight and loose knots along the vertical stem axis, and to keep the occlusion time of knots short and the knotty core inside the log small (Mäkinen and Hein 2006; Hein 2008). A high density stand results in higher competition, lower light availability, and increases self-pruning. Correspondingly, the amount of branches, the size of branches, and their occlusion time is reduced and the timber quality is high. For industrial processing the most important quality features are stem shape and stem length, but also branchiness and branch diameter, since the shape, length and branchiness of the logs clearly influence the yield but also the strength of the wood and their products. Furthermore, log prices generally increase with log diameter and even more with quality for larger-dimensioned logs (Ammer 2016). Timber quality is the main driver of timber prices for harvested logs for solid wood products or veneer, because timber quality can limit timber utilisation (Knoke et al. 2006; Bauhus et al. 2017). Therefore, it becomes important to estimate the clear wood content in standing trees in order to predict the value of each stem and correspondingly the value of the forest non-destructively prior to harvest. However, the estimation of the clear wood content is difficult to assess non-destructively and is usually not available before the trees are harvested or very time-consuming and labour-intensive. A promising approach may be the use of non-destructive terrestrial laser scanning (TLS) to assess external timber quality characteristics. Currently, a large number of individual tree attributes can be assessed using TLS. For example, the measurement of diameter at breast height (DBH), tree height, number of branches, crown base height, crown surface area, crown length, the volume of the standing tree, lean, sweep, taper, crookedness, asymmetry, the length of the clear bole, or deviations on the bark surface are described in literature (e.g., Simonse et al. 2003; Thies et al. 2004; Seidel et al. 2011a; Dassot et al. 2012; Kretschmer et al. 2013; Liang et al. 2014; Seidel et al. 2015). However, a subsequent prediction of the internal timber quality through external measures is usually lacking. In practice, foresters or procurement agents still mostly visually estimate timber quality and studies mainly focus on either external or internal timber quality.

For the above reasons, this thesis aimed for quantitatively assessing and evaluating the external and internal timber quality of 125 European beech trees from pure and mixed forest stands and examining the relationship between external and internal quality characteristics.

1.3. Objectives, research questions and hypotheses

A quality assessment on the standing tree conducted using TLS is compared to the conventional assessment by trained forest personnel and verified based on the agreement with the internal timber quality quantitatively assessed on sawn boards of the 125 target European beech trees. Furthermore, the influence of competition intensity as well as the influence of forest mixture type on timber quality is investigated. Lastly, the distribution of quality parameters within the trees is examined. The present study thereby focuses on the following questions:

(1) How does increasing competition affect the timber quality characteristics of European beech?
(2) What influence does neighbourhood species identity have on the timber quality characteristics of European beech?
(3) Are the quality features on the bark surface of the stem in accordance with the internal timber quality?
(4) How are timber quality features distributed along the horizontal and vertical stem axis?
(5) Do the numerous advantages of mixed forest stands come at the expense of quality?

In the upcoming Chapters 2 to 4 of this thesis the widely assumed positive relationship between the degree of competition and stem quality of the hardwood tree species European beech (Chapter 2, Chapter 3) as well as the assessment of external quality using TLS were tested

(Chapter 2). It was further investigated to what extent sawn timber quality of European beech is influenced by different mixture types in terms of neighbouring tree species identity (Chapter 3, Chapter 4). Moreover, it was examined whether or not and to what degree TLS-derived quality measures and a quality assessment from local district foresters on standing trees are related to sawn timber quality (Chapter 3). Lastly, the internal timber quality of European beech tree logs from mixed and pure forest stands was evaluated and compared (Chapter 4).

In detail, the following hypotheses are examined within the three main chapters:

Chapter 2

(2.1) The degree of competition from neighbouring trees affects quality-related external stem characteristics of European beech trees as inferred from non-destructive TLS-based measures.

Chapter 3

(3.1) Internal timber quality of European beech trees increases with increasing competition intensity.

(3.2) Internal timber quality of European beech trees differs depending on neighbouring species identity.

(3.3) Externally visible timber quality features are correlated with internal timber quality features.

(3.4) TLS as well as the quality assessment by the local district foresters can predict internal timber quality of European beech trees.

Chapter 4

(4.1) The timber quality attribute *knot surface* increases along the vertical stem axis and decreases along the horizontal stem axis as a results of the applied silvicultural treatment (keeping stands at high densities until self-pruning has reached around 8 m stem length, followed by cuttings that remove competitors from target tree while increasing their diameter growth).

(4.2) The timber quality attribute *knot surface* is smaller in pure compared to mixed beech stands due to higher competition intensity of beech itself.

1.4. Concept, material and methods

This thesis was realised under the joint project "Materialforschung Holz" funded by the Lower Saxony Ministry for Science and Culture. This joint project is a cooperation between the University of Göttingen (Faculties of Forestry, Chemistry and Physics) and the University of Applied Sciences and Arts Hildesheim/Holzminden/Göttingen (HAWK).

1.4.1. Study sites and study objects

The study sites for the conducted investigations presented in the chapters 2 to 4 belong to the forest department Reinhausen of the Lower Saxony State Forestry, in Germany. In detail, the study sites are located in the forest districts of Ebergötzen (formerly Husum; 51°40'55.5"N, 10°04'56.9"E), Reinhausen (51°26'55.9"N, 10°00'52.0"E), Reyershausen (51°35'38.2"N, 9°59'17.1"E), and Sattenhausen (51°30'41.7"N, 10°04'15.8"E). Of these forest sites, 125 vital and dominant to co-dominant European beech (*Fagus sylvatica* L.) sample trees with a DBH between 35 and 50 cm were selected from pure and mixed forest stands. In total, 50 sample trees were selected from pure forest stands and 75 sample trees from mixed forest stands. The mixed forest stands can be distinguished into three groups of 25 sample trees each: (i) European beech mixed with Norway spruce (*Picea abies* (L.) H. Karst.), (ii) European beech mixed with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and (iii) European beech mixed with European ash, Norway maple, or sycamore maple (*Fraxinus excelsior* L., *Acer platanoides L.,* and *Acer pseudoplatanus* L.). The selected sample trees from the mixed forest stands were surrounded by at least two trees of the admixed tree species that were classified as main competitors due to a similar DBH and a similar tree height. Furthermore, the neighbourhood of the sample trees also included European beech trees of different sizes from all tree classes according to Kraft (1884). Thereby, a wide and heterogeneous range of intra- and interspecific competitive pressure was enabled. Lastly, all forest stands were growing on rather nutrient-rich and well-drained soils on Triassic sandstone or limestone covered with loess and were managed as high forests.

1.4.2. Fieldwork

A sample circle with a radius of 15 m was arranged around each sample tree. For the sample trees and all neighbouring trees with a DBH $\geq$ 7 cm within this sample circle, the DBH, the height, the crown base height, and the distance between sample tree and neighbouring tree were measured and digitally documented using field map (IFER - Monitoring and Mapping Solutions, Ltd., Czech Republic). These measures were subsequently used to quantitatively determine

Hegyi's index of competition (cited in Bachmann 1998) for the current competitive situation using equation 1.1:

$$\text{Hegyi}_i = \sum_{j=1}^{n} \frac{\text{DBH}_j}{\text{DBH}_i * (\text{dist}_{ij} + 1)} \tag{1.1}$$

with sample tree (i), competitor tree (j), diameter at breast height (DBH, in cm), and the distance to between sample tree and competitor tree (dist, in m).

This was followed by applying terrestrial laser scanning (TLS) to all 125 sample trees to obtain quantitative in situ information on external timber quality features. A three-dimensional (3D) point cloud of each stem was created via TLS, using a Faro Focus 3D 120 laser scanner (Faro Technologies Inc., Lake Marry, USA). In accordance with breast height, the laser scanner was mounted on a tripod at approximately 1.30 m above the ground. In the horizontal direction, the Faro Focus 3D 120 covers a field of view of 360° and in the vertical direction of 300°. The maximum range is 120 m. In analogy to van der Zande et al. (2008), a multiple-scan approach was chosen. The trees were scanned from four different sites applying a total of four and a maximum of five scans per tree. The average distance of the laser scanner to the sample trees was 8.9 m (± 2.6 m standard deviation (SD)). Artificial checkerboard targets were pinned to neighbouring trees of each sample tree and used as reference objects to co-register the multiple scans as one single point cloud using Faro Scene software (FARO Technologies 2013).

The aligned point cloud of each sample tree was then exported as an xyz-file (file giving the x, y, and z coordinates within a 3D Cartesian coordinate system) and imported to Leica Cyclone software (Vers. 9.0.3, Leica Geosystems AG, Heerbrugg, Switzerland) to extract the single 125 stems manually from the point cloud of the forest scene. This means that all surroundings, including neighbouring trees, ground vegetation, and all other objects reflecting the laser beam without actually being part of the tree stem, were manually removed up to crown base height in the virtual 3D model of the forest. All dead branches occurring below crown base height were manually cut at a distance of 2 cm from the surrounding bark surface within the virtual 3D model of the single stem. The point clouds containing only the individual stems, ranging from the root collar up to the crown base height, were then exported as xyz-files and analysed using Mathematica (Wolfram Research, Champaign, Illinois, USA). External features, such as bark surface irregularities, stem roundness, lean, or sweep were quantitatively assessed (see Chapter 2). In addition to the quality assessment using TLS, a conventional quality assessment was conducted by the local district foresters at the standing sample trees in compliance with the German grading guidelines (RVR 2014). Using this quality grading guideline, the sample trees were hence virtually divided into the best possible stem sections (in m) of the quality classes A to D (Table 1.1, p. 26).

Following TLS, all 125 European beech sample trees were logged during a commercial harvest operation of the forest office of Reinhausen (Niedersächsische Landesforsten, Germany) and transported to the sawmill (Fehrensen GmbH, private limited company, Hann. Münden, Germany). At the sawmill, all sample trees were sawn into merchantable sections of 3, 4, or 5 m length and subsequently into boards with a thickness of min. 20 mm and max. 50 mm (Figure 1.1).

Figure 1.1 Five merchantable stem sections (3 m length) from the third sample tree (left) and an exemplary pile of sawn boards (right).

All boards were then captured photographically with a digital single-lens reflex camera (PENTAX K10D) mounted on a tripod. For each board, three to five images were taken over the entire length of the board. Thereby, one image covered approximately 1 m along the vertical stem axis. These single images of one individual board were manually merged using the software CorelDRAW© X4 (version 14.0.0.567, Corel Corporation 2008) and used for further timber quality analyses using Datinf® Measure (version 2.2, Datinf GmbH, Tübingen, Germany). A measuring tape placed besides the surface of the boards allowed for true-to-scale measurements of the board dimensions and of timber quality features using the merged photographs. Thus, the total length of each board, the board widths at 50 cm intervals, the total board surface area, the knot surfaces, and the discoloration surfaces were assessed for every single board (see Chapter 3) and used as quantitative measures for timber quality.

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Chapter 2

Competition improves quality-related external stem characteristics of *Fagus sylvatica*

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[*]Kirsten Höwler was responsible for literature and data collection, data analyses, presenting results and writing the manuscript. Dominik Seidel wrote algorithms for the procession of the laser scanning data and performed the computations. Christian Ammer, Peter Annighöfer, and Dominik Seidel supervised the manuscript and data analyses.

2. First study

Abstract

Accurate information on the timber quality of hardwoods is often lacking, in particular for standing trees. *In-situ* measurements of timber quality have the potential to improve the economic yield of a stand and may contribute to the optimal timing of a harvest and, in general, to improving forest management. Here, we used terrestrial laser scanning (TLS) to assess external timber quality metrics nondestructively. We investigated how competition intensity affected the metrics of 118 European beech (*Fagus sylvatica* L.) trees. We found that two newly developed TLS-based measures of external stem characteristics (*number of bark anomalies per metre* and *stem non-circularity*) were affected by competition intensity, suggesting that regulating competition levels may improve timber quality. Our study confirms empirical findings indicating a positive relationship between competition intensity and timber quality of European beech and offers a new methodology to assess external timber quality measures in the field objectively and nondestructively.

Keywords: bark anomalies, competition index, European beech, terrestrial laser scanning, timber quality.

2.1. Introduction

The conversion of pure forest stands to mixed stands is a major objective of forest management in several countries around the world (FAO 2001; von Lüpke et al. 2004). Mixed and uneven-aged stands are not only considered to be more resilient to disturbance regimes and more adaptive to changing climate conditions, but also believed to promote the biodiversity of flora and fauna. They can also be more productive than monospecific stands (MacNally et al. 2001; McElhinny et al. 2005; Neill and Puettmann 2013; Liang et al. 2016; Ammer 2017). In Germany, for example, forest conversion has already increased the proportion of deciduous forest by 7 % between 2002 and 2012 (BMEL 2018). However, the economic importance of hardwoods, as well as their processing and usability, has not yet been fully exploited (Möhring et al. 2008; BMELV 2011). In the future, the timber industry's high demand for softwood is predicted to contrast with the reduced supply of softwood through forest conversion (BMELV 2011). Decreased softwood supplies will need to be compensated for through, for example, replacement with hardwoods. Therefore, the industrial usability of hardwoods, which varies much more in timber quality than conifer softwoods, needs to be optimised so that future wood resources can be better utilised and the forest production value chain be enhanced (van Leeuwen et al. 2011; Kankare et al. 2014). For this purpose, accurate information on timber quality of hardwoods and on the factors influencing timber quality is needed. In the case of European beech (*Fagus sylvatica* L.) in particular, this information is lacking (Knoke et al. 2006). Moreover, information on inner wood quality is usually not available before the trees are felled (Stängle et al. 2014). However, it can be visually estimated prior to harvesting, e.g., by assessing quality features visible on the bark surface (growth morphology, knots, bark scars, etc.) (Richter 2010; Kankare et al. 2014). Also available are nondestructive quality-assessing acoustic technologies (i.e., acoustic velocity) to measure wood stiffness (Legg and Bradley 2016) or wood density measurements using minimally invasive microdrilling resistance measurements (Isik and Li 2003).

At sawmills, stem quality information can be obtained from X-ray computed tomography, three-dimensional (3D) laser scanning, or magnetic resonance imaging (e.g., Coates et al. 1998; Thomas and Thomas 2011; Krähenbühl et al. 2014; Stängle et al. 2014). Such information is then used to optimise sawing procedures, e.g., through log positioning, individual sawing patterns, edging, and trimming, which in turn reduce wood wastage (Rinnhofer et al. 2003; Stängle et al. 2015). Against this background, innovative and objective methods of assessing wood quality prior to harvesting are of great interest. A promising and pioneering approach could be the analysing of 3D laser scans of standing deciduous trees for quality assessment, a method that, to our knowledge, has rarely been tested to date.

Because log prices generally increase with log diameter and even more with quality for larger dimensioned logs (Knoke et al. 2006; Ammer 2016), it is crucial to be able to estimate the clear wood content in standing trees to ascertain appropriately the individual value of each stem and thus the value of the whole forest (Stängle et al. 2014).

Stem quality is determined mainly by genetic predisposition (Richter 2010) and external factors such as stand structure and stocking density, as they regulate local competition intensities within the population (Richter 2010; van Leeuwen et al. 2011; Merganič et al. 2016). Stocking density and hence competition are considered to affect the most important quality features underlying forest product values, i.e., stem shape and length, branchiness, and branch diameter (Hein 2008), as higher competition pressure results in increased self-pruning and hence lower branchiness (Mäkinen and Hein 2006; Hein 2008). From a management point of view, it is important to note that both stocking density and competition can be controlled through silvicultural measures (Pretzsch 2009).

At present, terrestrial laser scanning (TLS) has been used for measuring dimensional attributes such as diameter at breast height (DBH), tree height, crown length, and crown base height (e.g., Seidel et al. 2015), as well as the volume of standing trees (Dassot et al. 2012), or quality attributes such as curvature, lean, sweep, taper, the length of the clear bole, or asymmetry of the tree (Simonse et al. 2003; Thies et al. 2004; Seidel et al. 2011a; Liang et al. 2014). In addition, Kretschmer et al. (2013) have described a method based on TLS data to detect deviations of the bark surface such as bark scars and branch knots. However, an automated, quantitative, and operationally nondestructive method for assessing external wood quality measures of standing trees is currently lacking. Once developed, such a method could be a viable means of improving forest inventories as quality assessment could be included. Consequently, in this study, we have assessed a newly developed TLS-based methodology for describing external timber quality attributes. The widely assumed positive relationship between the degree of competition and the stem quality of hardwood trees was tested and resulted in the following hypothesis: the degree of competition from neighbouring trees affects quality-related external stem characteristics of European beech trees as inferred from nondestructive TLS-based measures.

2.2. Materials and methods

2.2.1. Study area and study objects

This study was conducted in the forest districts of Ebergötzen (formerly Husum) (51°40’55.5”N, 10°04’56.9”E), Reinhausen (51°26’55.9”N, 10°00’52.0”E), Reyershausen (51°35’38.2”N, 9°59’17.1”E), and Sattenhausen (51°30’41.7”N, 10°04’15.8”E), all belonging to the forestry department Reinhausen in Lower Saxony, Germany (detailed stand description in Table 2.1). A total of 118 European beech trees were selected as study trees. The trees grew in three mixed stands and one pure stand, all managed as “high forests” (a forest originating from generative regeneration, managed in long production cycles for timber production).

In the mixed stands, the selected European beech trees were surrounded by (*i*) Norway spruce (*Picea abies* (L.) H. Karst.), (*ii*) Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), or (*iii*) hardwoods (*Acer* spp., *Fraxinus excelsior* L., *Ulmus glabra* Huds., and others) and some conspecifics. All 118 study trees were selected according to the following criteria: (*i*) DBH (1.3 m above the ground) between 35 to 50 cm and (*ii*) dominant to co-dominant trees (tree classes 1-3 according to Kraft (1884)).

Mean DBH of the 118 study trees was 42.15 cm (±6.24 cm standard deviation (SD)), and mean height was 29.81 m (±3.04 m SD). We systematically selected trees exposed to a wide range of competitive pressures as indicated by the presence of differently sized neighbouring trees at varying intertree distances to local competitors.

2.2.2. Fieldwork

Circular sample plots (radius = 15 m) were established around each target tree. Within these sample plots, the metrics DBH, crown base height (defined as the height of the first living branch), and total height were measured for all trees with a DBH ≥ 7 cm, assuming that these trees were potential competitors for the respective target tree. DBH, crown base height, and total height of these neighbouring trees were measured using a diameter tape and a Vertex IV sonic clinometer (Haglöf Sweden AB, Västernorrland, Sweden). The spatial positions of all competitors of each target tree were measured with the Field-Map instrument-software package (IFER - Monitoring and Mapping Solutions, Ltd., Czech Republic). To determine the competition intensity surrounding each target tree, the diameter and the spatial measurements were used to calculate three competition indices (CI) for each target tree according to Hegyi (1974) (eq. 2.1), Martin and Ek (1984) (eq. 2.2), and Elliott and Vose (1995) (eq. 2.3):

$$\text{Hegyi}_i = \sum_{j=1}^{n} \frac{\text{DBH}_j}{\text{DBH}_i * (\text{dist}_{ij}+1)} \tag{2.1}$$

$$\text{MartinEk}_i = \sum_{j=1}^{n} \frac{\text{DBH}_j}{\text{DBH}_i} * e^{-\left[\frac{16*\text{Dist}_{ij}}{(\text{DBH}_i + \text{DBH}_j)}\right]} \tag{2.2}$$

$$\text{ElliottVose}_i = \sum_{j=1}^{n} \frac{h_j}{\text{DBH}_i * \text{dist}_{ij}} \tag{2.3}$$

with target tree *i*, competitor tree *j*, diameter at breast height (DBH), total tree height (*h*), and distance between target tree and competitor tree (dist) within radii encompassing 5, 7.5, 10, 12.5, and 15 m (see Hartmann et al. 2009). We decided to test three competition indices in order to evaluate the explanatory power of the approaches presented. Hegyi (1974), Martin and Ek (1984), and Elliott and Vose (1995) were chosen because no crown information was available yet it was necessary for various other competition indices (e.g., Bella 1971; Tomé and Burkhart 1989; Biging and Dobbertin 1992; Pretzsch 1995).

To obtain quantitative *in-situ* information on timber quality features of the 118 target trees, a 3D point cloud of each stem was created via TLS. Scans were acquired between September and November 2015, using a Faro Focus 3D 120 laser scanner (Faro Technologies, Inc., Lake Mary, Florida, USA). The laser scanner was mounted on a tripod at approximately 1.3 m (breast height) above the ground, covering a field of view of 360° in a horizontal direction and 300° in a vertical direction (maximum distance of 120 m). The angular step width was set at 0.035°, which equates to a resolution of 10,240 measurements per 360° or a total spatial resolution of approximately 44 million measurements per scan.

A multiple-scan approach with four scans per tree was chosen to capture the tree stems from all sides (see exemplary scan arrangement in Figure 2.1, according to van der Zande et al. (2008)). The mean distance between the target trees and the laser scanner was 8.9 m (±2.6 m SD). In order to co-register these four scans (four point clouds from four different perspectives, respectively, for one sample tree) as one single point cloud, 10-20 artificial checkerboard targets (tie points on DIN-A4 paper) were used. The sheets of paper were pinned to stems of surrounding trees around each sample tree and used as reference objects for the co-registration process in Faro Scene software (Faro Technologies, Inc.).

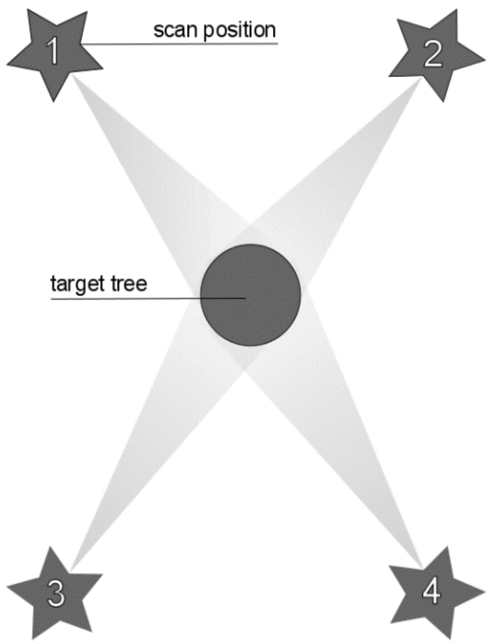

Figure 2.1 Schematic scan arrangement around an exemplary study tree following van der Zande et al. (2008).

Table 2.1 Stand description of the four study sites Sattenhausen, Reinhausen, Ebergötzen (formerly Husum), and Reyershausen by district. APs, *Acer pseudoplatanus*; APl, *Acer platanoides*; BP, *Betula pendula*; CB, *Carpinus betulus*; FE, *Fraxinus excelsior*; FS, *Fagus sylvatica*; HQH, high quality hardwood; LD, *Larix decidua*; PiA, *Picea abies*; PM, *Pseudotsuga menziesii*; PN, *Pinus nigra*; PrA, *Prunus avium*; PS, *Pinus sylvestris*; QP, *Quercus petrea*; QR, *Quercus robur*; ST, *Sorbus torminalis*; UG, *Ulmus glabra*.

		Sattenhausen				**Reinhausen**							**Ebergötzen**		**Reyershausen**		
		1024	1033	1039	1043	10	14	16	18a	18e	34	37	1065	1068	3024	3025	3027
Area (ha)		11.1	8.7	4.7	3.9	14.6	13.9	1.6	1.6	1.1	15.6	1.3	6.2	4.0	19.1	13.8	18.1
Elevation (m a.s.l.)		251-300	301-350	351-400	251-300	301-350	251-300	251-300	251-300	251-300	251-300	251-300	151-200		351-400		
Site conditions		Triassic limestone				Triassic sandstone							Triassic sandstone		Triassic limestone		
Tree mixture		FS* & HQH*	FS & HQH	FS & HQH	FS & HQH	FS & LD	FS & PiA	PM & PiA	FS	FS & PiA	FS & PiA	PM & PiA	FS & PiA	FS & PiA	FS & HQH	FS & HQH	FS & HQH
Main tree species	Species	FS	FS	FS	FS	FS	FS	PM	FS	FS	FS	PM	FS	FS	FS	FS	FS
	Age	90	111	93	73	79	72	53	93	90	85	62	88	88	91	85	80
	Standing volume (m³/ha)	337	361	300	159	168	215	316	375	172	316	188	229	186	267	221	224
	Share (%)	85	84	70	45	48	83	78	100	50	85	45	65	53	85	74	73
	Top height (m)	33.1	33.7	34.2	29.6	30.8	25.5	32.6	31.3	27.4	32.0	32.3	30.2	30.2	27.4	26.4	25.3
	Mean DBH (cm)	34	39	36	26	29	22	38	33	28	31	39	31	31	28	26	24
Admixed tree species (age (years), standing volume (m³/ha))		FE* (90,30)	FE (111,36)	FE (93,81)	FE (73,152)	LD (71,80)	PiA (63,50)	PiA (59,85)	-	PiA (94,195)	PiA (80,57)	PiA (59,174)	PiA (88,125)	PiA (88,114)	FE (91,37)	FE (85,43)	FE (70,39)
		LD* (74,18)	APs (111,5)	APs (93,16)	PS* (126,28)	PiA* (76,112)	PS (66,9)	FS (62,13)	-	PS (166,0)	LD (80,19)	FS (68, 40)	LD (88,42)	LD (88,72)	APs (91,7)	Aps (85,26)	APs (70,15)
		APs* (90,3)	UG* (111,8)	UG (93,0)	PN* (126,28)	PM* (75,31)	BP* (72,3)	-	-	LD (166, 35)	-	-	CB* (88,11)	QR (78,19)	UG (91,2)	APl (85,2)	LD (60,16)
		ST* (90,0)	ST (111, 8)	-	-	QP* (184, 0)	LD (66,8)	-	-	-	-	-	QR* (88,5)	FE (88,8)	-	UG (85,2)	PrA* (70,8)
		-	-	-	-	-	-	-	-	-	-	-	-	-	-		UG (70,3)
No. of target trees		5	4	4	3	10	20	5	10	5	5	4	5	5	15	5	13
Heavy crown thinning (m³/ha)	2011	-	-	-	-	29.7	-	-	-	-	-	-	-	-	46.8	70.0	29.6
	2012	-	-	-	-	-	-	-	-	-	-	12.1	-	-	33.4	-	17.2
	2013	93.2	-	-	-	-	-	3.7	-	-	-	-	-	-	34.4	18.5	175.0
	2014	-	-	-	-	-	-	-	-	-	-	-	-	-	69.8	56.8	36.4
	2015	-	54.0	-	-	10.5	-	-	-	62.0	12.2	-	-	15.9	20.9	-	94.0
	2016	-	-	10.3	7.3	-	-	-	-	-	-	-	-	-	0.7	-	-

2.2.3. Postprocessing TLS data

2.2.3.1. Point cloud preprocessing

The combined point cloud of each sample tree was then exported as an *xyz* file (file giving the *x*, *y*, and *z* coordinates within a 3D Cartesian coordinate system) and imported to Leica Cyclone software (Vers. 9.0.3, Leica Geosystems AG, Heerbrugg, Switzerland) to extract the single 118 stems manually from the point cloud of the forest scene. This means that all surroundings, including neighbouring trees, ground vegetation, and all other objects reflecting the laser beam without actually being part of the tree stem, were manually removed up to crown base height in the virtual 3D model of the forest. All dead branches occurring below crown base height were manually cut at a distance of 2 cm from the surrounding bark surface within the virtual 3D model of the single stem. The point clouds containing only the individual stems, ranging from the root collar up to the crown base height (see Figure 2.2 as an example), were then exported as *xyz* files for further processing.

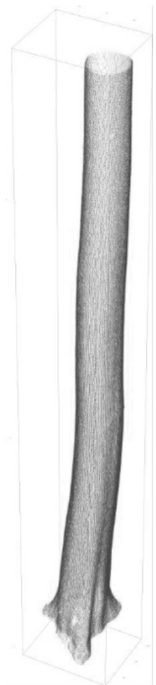

Figure 2.2 Exemplary point cloud of a sample tree stem from root collar to crown base height.

2.2.3.2. Point cloud processing

All *xyz* files of the stems of the trees were processed based on a newly developed algorithm written in the software Mathematica (Wolfram Research, Champaign, Illinois, USA). First, all tree stem sections were stratified into 5 m long sections until the remainder was shorter than 5 m. We chose a segmentation of the stems into 5 m sections because the shortest stem of the 118 sample trees had a length of 4.49 m. Accordingly, longer sections were not available for all stems and a comparison of the economically important first 5 m sections for all 118 sample trees was enabled. None of the manually separated tree point clouds had a branch-free bole of more than 15 m in length, resulting in a maximum of three 5 m sections per tree. Then, for each section of a stem, the same procedure was performed: a point cloud grid of 1.75 cm resolution was used to homogenise the point cloud of all trees in accordance with Seidel et al. (2011b). Variations in point cloud densities among trees scanned with identical scan settings naturally result from varying scanner-to-tree distances, varying overlapping of data from different scan positions, and occlusion effects due to understory vegetation. We chose a 1.75 cm grid size for the following reason: the average height of the study trees was 29.81 m (from root collar to the top of the tree), measured using the Haglöf Vertex IV. Assuming this to be the maximum distance between the scanner and a point on the tree yields a maximum beam-to-beam distance of 1.75 cm for the scan settings. We argue that a point cloud grid that covers this maximum point-to-point distance is conservative and should sufficiently homogenise the shorter distances in the lower section of the tree used in our study (maximum of 15 m stem length). In addition, one should take into account that the top of all 15 m tall sections of the trees is always more than 15 m away from the scanner position, as the scanner is not located directly under the tree but at varying distances away from it. One should also bear in mind that rougher point cloud grid resolutions might hamper the detection of stem characteristics of interest.

Horizontal 1.75 cm thick layers (representing "stem discs" of 1.75 cm thickness) were taken from the homogenised point clouds every 1.75 cm along the stem. We decided to use horizontal layers as we considered this as the "saw-mill-like" approach, because trees are also cut horizontally when processed at the mill. For each layer, a circle was fitted to the points based on QR decomposition, a factorization of a matrix with "Q" as the orthogonal and "R" as the upper triangular matrix (Gentle 1998; Seidel and Ammer 2014). In the present study, we defined a minimum of 20 points for a reliable circle fit, and this rule was not violated a single time due to the high resolution of the original point cloud. Then the diameter, centre coordinates, and respective height above ground of every fitted circle were stored.

For the lowest section (0-5 m), we considered the diameter of the layer measured at 1.3 m above the ground to be the *DBH* (from here on *DBH* refers to the scan-based measurement instead of the diameter tape based measurements described previously). The difference between the heights of the uppermost and lowermost fitted circles was considered to be the length of the stem within a section (Figure 2.3, denoted as *a*).

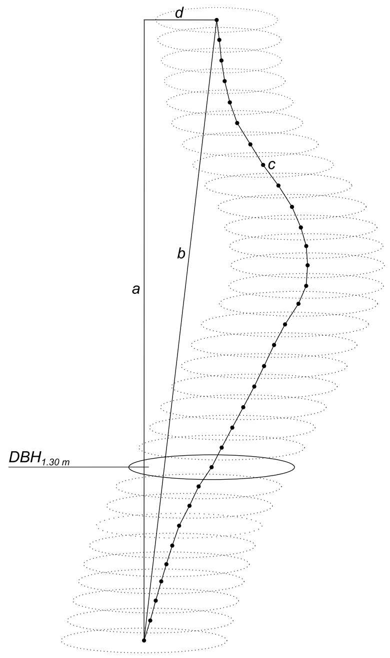

Figure 2.3 Schematic draft of the fitted circles along the vertical axis of a stem section with measures *a, b, c*, and *d* used to calculate *lean, sweep*, and *DBH*.

We calculated the total lean of the stem sections based on the horizontal difference between the centres of the lowermost circle and the uppermost circle (Figure 2.3, denoted as *d*). This value was divided by the total length of the section to calculate a length-independent measure of *lean per metre*. Total sweep of the stem was determined to be the ratio of the shortest distance between the centres of the lowermost and uppermost circles (Figure 2.3, denoted as *b*) and the sum of the shortest distances between the centres of all consecutive circles along the vertical direction (Figure 2.3, denoted as *c*). Total sweep was converted to *sweep per metre* by dividing it by the length of the stem section.

In the following, we calculated several scan-based measures that were intuitively promising to enable a detailed description of external quality-related attributes to be made. For every point in every layer and in every stem section, we determined the absolute difference between the distance from the circle centre to the point and the radius of the circle fitted to the respective layer in which the point was located (Figure 2.4a). The mean of these absolute distances was calculated for each height layer. The median of all height layers was finally considered a measure of *stem non-circularity* of the stem section. The standard deviation of all height layers per stem section was considered as a measure of variability in *stem non-circularity* along the vertical stem axis.

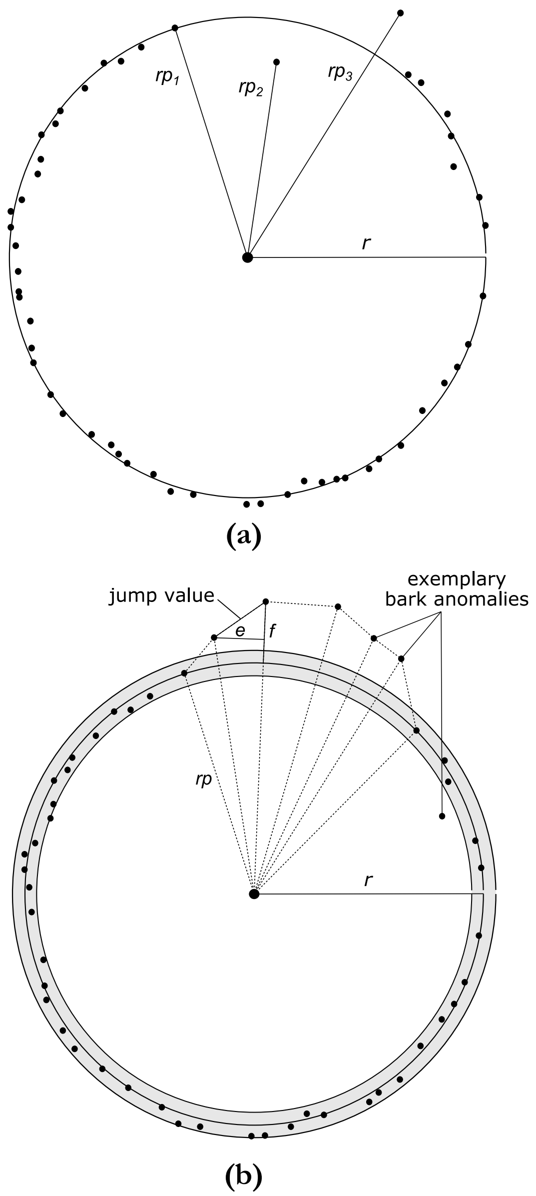

Figure 2.4 **(a)** Exemplary circle fitted through the points in a certain horizontal height layer with the centre of the circle and three exemplary points (rp_1, rp_2, and rp_3) shown. Other circumferential points in the circle are exemplary hits of the laser beam on the surface of the trees. If every point had a radius that equals the radius of the circle (such as rp_1), the tree stem cross section would be perfectly circular. The greater the mean of all absolute differences ($|r - rp_i|$) was, the less circular the tree was. **(b)** Exemplary cross section illustrating "jump distance" (*e*) and "jump height" (*f*). The "jump value" between two neighbouring points was defined as the ratio between *e* and *f*; *r* indicates the radius of the fitted circle; and *rp* is the radius to a given point of the cross section. The grey shaded area shows mean ± standard deviation. All points exceeding this area are counted as *bark anomalies*.

Afterwards, for every cross section, we sorted the points according to their azimuthal angle if measured from the centre of the cross section (defined as the centre of the fitted circle). Then, the distance between every two points in the sorted list of points was determined as the Euclidean distance of the *x* and *y* coordinates. This measure was considered the "jump distance" between two points. Due to occlusion effects in the scan data, the "jump distance" could potentially be larger than the scan settings would suggest. "Jump distance" was used to calculate a so-called “jump value”, defined as the ratio of “jump distance” (Figure 2.4b, denoted as *e*) to “jump height” (Figure 2.4b, denoted as *f*), with the latter being the difference in radius (measured from the circle centre) between two neighbouring points. This approach corrects for unequal “jump distances” due to missing data (occluded parts of the stem). The mean “jump value” can be considered a measure of irregularity in the tree stem surface. Hence, we considered those points with “jump values” larger or smaller than the mean ± standard deviation of the respective cross section as “bark anomalies” (branch scars, bark damages, etc.) (cf. Figure 2.4b). “Bark anomalies” thus count all points with a position that deviates “more than usual” from the fitted circle. We finally calculated the *number of bark anomalies per metre* for the stems, as not all stems had a complete 5 m segment remaining in the higher sections (5-10 and 10-15 m).

2.2.4. Statistical analysis

To investigate the effect of competition on external quality-related stem attributes, we used the metrics *number of bark anomalies per metre, lean per metre*, *sweep per metre*, and *stem non-circularity*. First, we applied the Shapiro-Wilk test to determine if the data were normally distributed.

Because a normal distribution of the data could not be assumed, Spearman’s rank correlations between the competition indices and the various attributes were calculated for five different competition radii (5, 7.5, 10, 12.5, and 15 m). The significance of correlations was tested for all attributes and all three stem sections (0-5, 5-10, and 10-15 m). All three calculated competition indices were highly correlated ($p < 0.001$, $0.77 \leq \rho \leq 0.90$; Table 2.2). Hence, we chose the Hegyi index for the following reasons. First, the competition index according to Elliott and Vose (1995) uses the height of the competitor tree to calculate competition intensity. Unfortunately, the height was not available for all competitor trees as some of them were harvested in earlier thinning procedures; therefore, the competition indices according to Hegyi (1974) and to Martin and Ek (1984) were preferred to that of Elliott and Vose (1995). Secondly, the Hegyi index (next to Pretzsch (1995) and Biging and Dobbertin (1992)) was described as most effective to quantify individual competition strength (Bachmann 1998). All quality attributes significantly related to competition within a competition radius encompassing 7.5 m (a radius of 7.5 m was chosen as this radius provided the best fit to the data) were used for further analysis. To analyse the intensity of the competition effect on stem attributes, regression analysis was applied. The data structure suggested exponential relationships (verified through generalised additive models (GAM), data not shown) with non-normal errors, which is why we used generalised linear models (GLM) to describe the relationship between predictor and response variables. A gamma error distribution was suspected from the data (Crawley 2007).

The significance level was $p < 0.05$ for all tests. All statistical analyses were performed using the free software environment R (Version 3.1.3, R Core Team 2015).

Table 2.2 Spearman's correlation (ρ) and *p* values for the three competition indices Hegyi (1974), Elliott and Vose (1995), and Martin and Ek (1984).

	Hegyi		**Elliott and Vose**		**Martin and Ek**	
	ρ	*p* value	ρ	*p* value	ρ	*p* value
Hegyi	-	-	0.87	< 0.001	0.90	< 0.001
Elliott and Vose	0.87	< 0.001	-	-	0.77	< 0.001
Martin and Ek	0.90	< 0.001	0.77	< 0.001	-	-

2.3. Results

2.3.1. Quality metrics

The distribution of the *number of bark anomalies per metre* for all 118 study trees and all three stem sections showed that the number decreased from the first section (0-5 m) with 1173.2 (median) ± 211.7 (SD) to the last section (10-15 m) with 765.8 (median) ± 250.1 (SD) (Figure 2.5). Values for *stem non-circularity (mean)* decreased from the first section (0-5 m) to the second section (5-10 m) and increased from the second section to the third section (10-15 m) (0-5 m, 0.009 (mean) ± 0.002 (SD); 5-10 m, 0.008 ± 0.002; 10-15 m, 0.008 ± 0.003) (Figure 2.6).

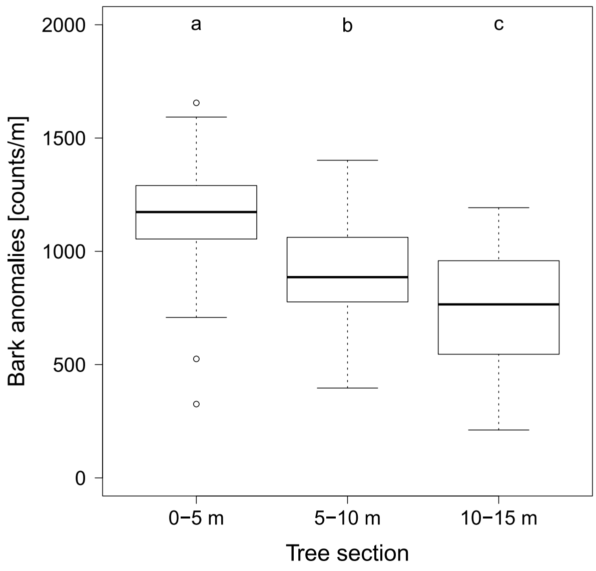

Figure 2.5 Range of *bark anomalies per metre* for all 118 sample trees within each 5 m tree section. Letters (*a*, *b*, and *c*) indicate significant differences between the 5 m sections at $p < 0.05$ (two-sided, nonparameteric, pairwise Wilcoxon test with Bonferroni correction).

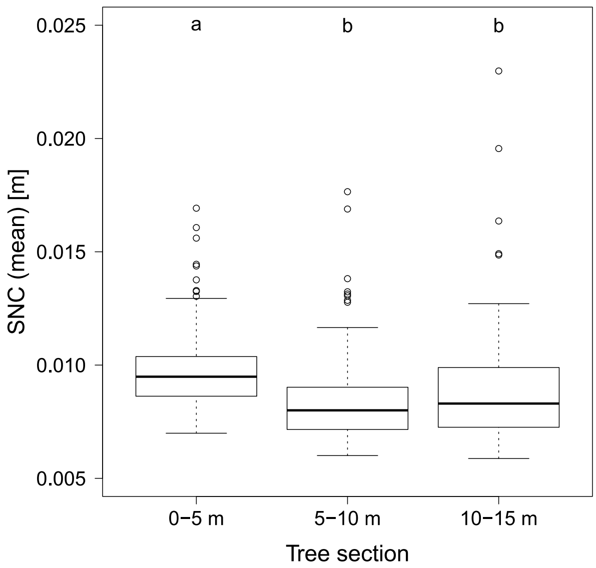

Figure 2.6 Range of *stem non-circularity (mean)* for all 118 sample trees within each 5 m tree section. Letters (*a* and *b*) indicate significant differences between the 5 m sections at $p < 0.05$ (two-sided, nonparameteric, pairwise Wilcoxon test with Bonferroni correction).

2.3.2. Effect of competition intensity on quality metrics

Competition intensity significantly influenced the quality metrics *number of bark anomalies per metre* and *stem non-circularity*. We found significant negative correlations between the Hegyi values (1.25 ± 0.54, mean ± SD) and the *number of bark anomalies per metre* and *stem non-circularity (mean)* (Table 2.3). *Stem non-circularity (mean)* significantly decreased with an increasing Hegyi index for the lowermost tree section (0-5 m, $p < 0.01$, radius 7.5 m). The *number of bark anomalies per metre* was also significantly correlated to the competition index and decreased with an increasing Hegyi index (0-5 m, 5-10 m, 10-15 m). Furthermore, we found significant positive correlation between the Hegyi values and *sweep per metre* and *lean per metre* within smaller competition radii (5 m and 7.5 m) and only for the first stem section (0-5 m) (Table 2.3).

Table 2.3 Spearman's correlation (ρ) and p values for the correlation between the Hegyi index and stem attributes for different radii (5, 7.5, 10, and 12.5 m) and all three stem sections (0-5 m, 5-10 m, 10-15 m).

Stem section		***p* value**				**ρ**			
		5 m	7.5 m	10 m	12.5 m	5 m	7.5 m	10 m	12.5 m
0–5 m	**BA_{pm}***	0.003	<0.001	<0.001	<0.001	-0.27	-0.33	-0.47	-0.51
	SNC_{mean}*	0.045	0.002	0.040	0.028	-0.18	-0.29	-0.19	-0.20
	SNC_{med}*	0.079	0.006	0.066	0.087	-0.16	-0.25	-0.17	-0.16
	L_{pm}*	0.005	0.051	>0.1	>0.1	0.25	0.18	0.09	0.10
	S_{pm}*	<0.001	0.016	0.088	0.064	0.30	0.22	0.16	0.17
5–10 m	**BA_{pm}**	0.003	<0.001	<0.001	<0.001	-0.28	-0.32	-0.38	-0.43
	SNC_{mean}	>0.1	0.046	>0.1	>0.1	-0.09	-0.18	-0.07	-0.03
	SNC_{med}	>0.1	0.033	>0.1	>0.1	-0.08	-0.20	-0.07	-0.03
	L_{pm}	>0.1	>0.1	>0.1	>0.1	0.04	0.06	0.03	0.08
	S_{pm}	>0.1	>0.1	>0.1	>0.1	<0.01	0.01	0.10	0.12
10–15 m	**BA_{pm}**	0.002	0.001	<0.001	<0.001	-0.34	-0.37	-0.48	-0.51
	SNC_{mean}	>0.1	0.039	>0.1	>0.1	0.14	0.22	0.13	0.18
	SNC_{med}	>0.1	0.043	>0.1	>0.1	0.13	0.22	0.11	0.15
	L_{pm}	>0.1	>0.1	>0.1	>0.1	0.01	0.03	0.12	0.12
	S_{pm}	>0.1	>0.1	>0.1	>0.1	-0.02	0.01	0.16	0.14

*Shaded areas: light gray, $p < 0.05$ and (or) $0.2 \leq \rho \leq 0.3$; medium gray, $p < 0.01$ and (or) $0.3 \leq \rho \leq 0.4$; dark gray, $p < 0.001$ and (or) $\rho > 0.4$. BA_{pm}, bark anomalies per metre; SNC_{mean}, stem non-circularity (mean); SNC_{med}, stem non-circularity (median); L_{pm}, lean per metre; S_{pm}, sweep per metre.

Additionally, Spearman's correlations for quality attributes and competition intensity within varying radii revealed that the greater the radii (12.5 m), the higher the coefficient of correlation (ρ) between Hegyi index and *number of bark anomalies per metre* (e.g., increasing ρ from -0.27 for a 5 m radius to -0.51 for a 12.5 m radius for the first stem section). This was found for all three stem sections. For a greater radius (15 m), the coefficient of correlation decreased (data not shown).

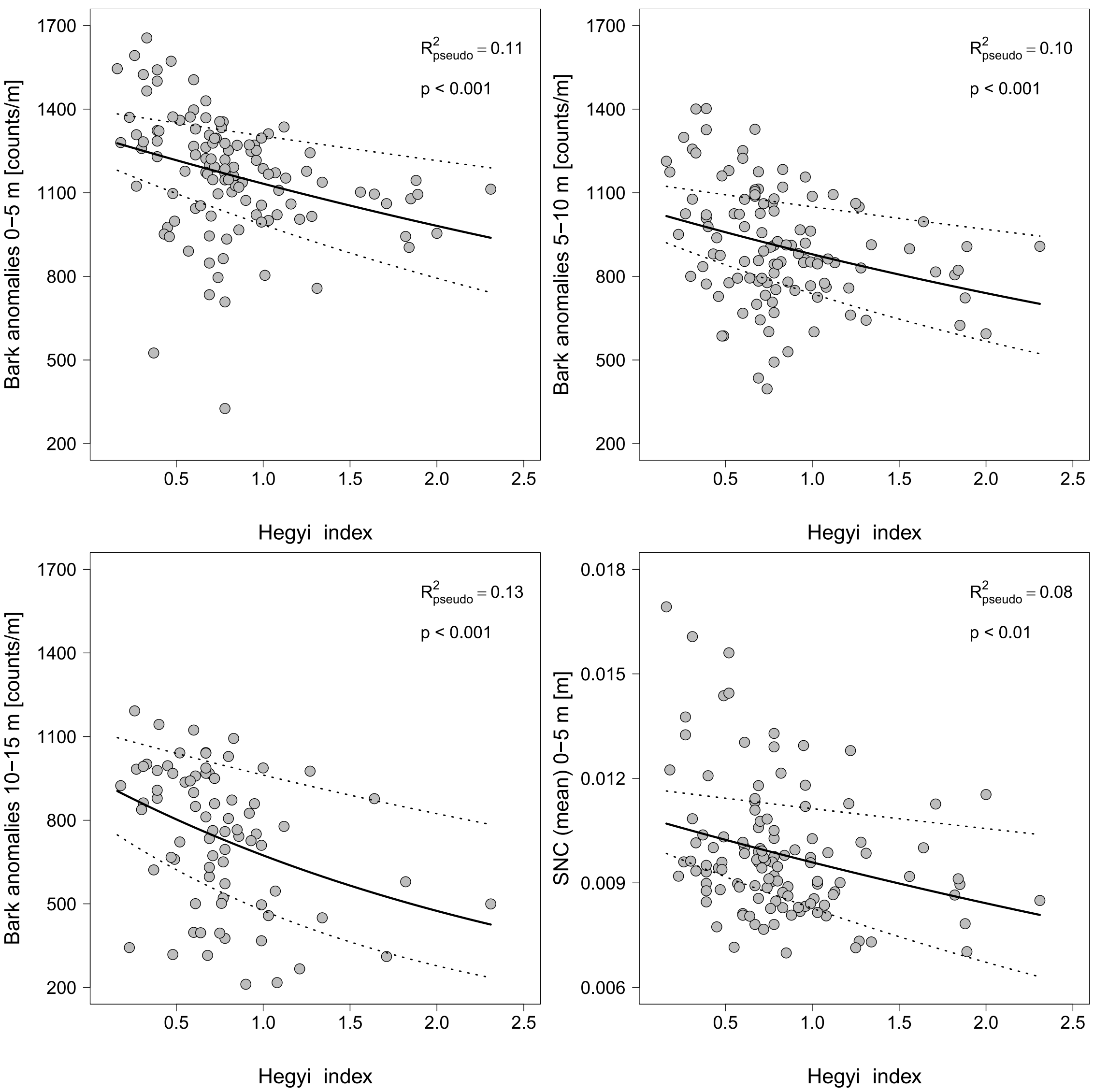

Figure 2.7 Relationship between the degree of competition (radius 7.5 m) on the target trees and the quality-related stem attribute *bark anomalies per metre* and *stem non-circularity (mean)* (SNC). Dotted lines show the 95% confidence interval.

In accordance with Spearman's correlation results, the GLM analysis with the quality attributes as response variables and the Hegyi index as explanatory variable, confirmed that competition intensity (radius 7.5 m) significantly influenced the number of bark anomalies per metre and stem non-circularity (mean) (Table 2.4; Figure 2.7). For the first tree segment (0-5 m), stem non-circularity (mean) was also influenced by competition intensity. The number of bark anomalies per metre decreased for all three tree sections (0-5 m, 5-10 m, 10-15 m) with an increasing Hegyi index (Table 2.4; Figure 2.7).

Table 2.4 Summary of the generalised linear models for the response variables (model) dependent on the Hegyi index (radius 7.5 m) as explanatory variable for different stem sections, showing model significance (*p* value), pseudo R squared (R^2_{pseudo}), parameter estimates (estimate) with their standard errors (SE), and model deviance for the intercept model (null deviance) and the full model (residual deviance) and their degrees of freedom (df).

Stem section	Model	*p* value	R^2_{pseudo}	Estimate	SE	Null deviance	Residual deviance
0-5 m	BA_{pm}*	< 0.001	0.11	-0.14	0.04	4.63 on 144 df	4.21 on 113 df
	SNC_{med}*	< 0.01	0.08	-0.13	0.04	3.84 on 177 df	3.49 on 116 df
5-10 m	BA_{pm}	< 0.001	0.10	-0.17	0.05	6.19 on 113 df	5.60 on 112 df
10-15 m	BA_{pm}	< 0.001	0.13	-0.35	0.10	11.15 on 76 df	9.90 on 75 df

*BA_{pm}, bark anomalies per metre; SNC_{med}, stem non-circularity (median).

2.4. Discussion

2.4.1. Relevance of the observed relationships for forest management

The newly introduced attribute *number of bark anomalies per metre* is a measure of the irregularity of the stem surface, which is principally affected by branchiness, as well as stem damage leading to bark scars, bumps, or seams (Richter 2010). It is well known that stand density is negatively related to branch size and positively related to self-pruning intensity (Ballard and Long 1988; Mäkinen 1999, 2002; Mäkinen and Hein 2006), as stand density stress can lead to high competitive pressure in European beech stands (Ammer et al. 2005), which undergo pronounced self-thinning at high densities, resulting in (*i*) high mortality of suppressed trees (Pretzsch and Biber 2005) and, as mentioned previously, (*ii*) rapid natural pruning of all trees (Weidig et al. 2014). In studying the second-log branches of redwood trees, Kirk and Berrill (2016) observed that the diameter of the largest branch measured was more negatively influenced by the branches of its immediate neighbouring tree as these neighbouring branches came closer. Hence, a decrease in the *number of bark anomalies per metre* is most likely due to the fact that increased competition resulted from higher stem densities or larger neighbours, both leading to reduced radiation levels of the lower crown layer. This, in turn, promoted self-pruning within the lower stem section. Consequently, resulting logs will have fewer knots in the sawn wood surface and therefore a higher timber quality (cf. Richter 2010). However, even after bark wounds have been occluded completely, bark anomalies (which we quantified based on the *number of bark anomalies per metre*) remain a distinctive sign for reduced timber quality (Hecht et al. 2015). Among others, the occurrence of red heartwood may be increased as may the number of knots influencing the strength of wood as knots are predetermined breaking points (e.g., Mäkinen and Hein 2006; Hein 2008; Richter 2010). Other authors also showed that the economic yield from sawn wood of European beech is most strongly impaired by knots that are visible on the sawn wood surface (e.g., Stängle et al. 2015). In this context, one has to consider that increasing stand density impairs secondary growth and the achievement of valuable dimensions (Zingg and Ramp 2003; Mäkinen and Hein 2006), which in turn leads to longer production periods.

The decrease in the *number of bark anomalies per metre* from the lowest to the highest 5 m section is likely attributable to the fact that the density of points within the point cloud grids was lower for the third and highest tree section (10-15 m) due to occlusion effects by neighbouring trees.

The *stem non-circularity* of the cross section of a stem is an important characteristic for timber quality (increasing circularity should result in increased timber value; see, e.g., Zingg and Ramp 2003). Reduced circularity reduces the yield due to a high proportion of cutoffs during the sawing procedure (Richter 2010). One has to consider that horizontal layers were used to determine *stem non-circularity*. Inferentially, a leaned circular stem shows an elliptical circle. This may influence the results of *stem non-circularity (mean)* and also of the *number of bark anomalies per metre*. Differences in *stem non-circularity (mean)* among the three height strata are supposedly determined by the natural growth of the trees, with the root collar in the first stem section (0-5 m) and the crown base within the third stem section (10-15 m).

The other tested quality attributes, *lean per metre* and *sweep per metre*, were significantly correlated to Hegyi values only within smaller competition radii (5 m, 7.5 m). We argue that this may be a result of effects of the immediate surroundings of a tree, as only competitors in close proximity directly affect the growing space availability of target trees. It is known from other studies (Hartmann et al. 2009) that close conspecific neighbours determine radial growth. *Lean per metre* and *sweep per metre* may be much more sensitive to growing space availability than to *stem non-circularity* or the *number of bark anomalies per metre* (which may be tree species specific and may not be valid for other tree species).

The range of competition intensity induced by different tree species surrounding the target trees was quite variable in this study. In particular, the competition range of the mixed neighbourhoods was quite narrow and the intensity was low compared with the competition range induced by conspecific beech trees. This supports earlier findings reporting that under given site conditions, intraspecific competition of beech is much stronger than interspecific interference (Dieler and Pretzsch 2013; Metz et al. 2016). Against this background, we refrained from comparing pure and mixed neighbourhoods after statistical evaluation. This important aspect will be the focus of future research. However, it seems that empiric findings showing higher stem qualities for beech growing in pure rather than in mixed stands can be attributed to differences in competition intensity. It has been shown (e.g., Metz et al. 2013) that beech is exposed to much higher competition in monospecific stands compared with interspecific neighbourhoods.

2.4.2. Strength of the observed relationships between competition and external quality attributes

Despite significant relationships identified with the generalised linear models, local competition explained only a rather small proportion of variability observed for the measures *number of bark anomalies per metre* and *stem non-circularity*. We argue that this may be due to a combination of several issues.

Firstly, all four study sites are managed as commercial forests and correspondingly all study trees were of "average" or "good" quality (quality grades B and only a minor proportion of grade C according to RVR (2014)); no study tree was of "poor" quality. Considering this narrow range of qualities, a rather weak explanatory power may not be surprising and one may argue that our data show that the presented methodology is actually sensitive to small differences in external quality attributes of European beech. However, future studies should also include European beech trees of poor timber quality.

Secondly, the Hegyi index and the other two competition indices used in our study (Martin and Ek 1984; Elliott and Vose 1995) are based on tree size (DBH, height) and distance to the neighbouring trees. They do not use crown variables for the calculation of competition intensity. A more complex index (e.g., Bella 1971; Tomé and Burkhart 1989; Biging and Dobbertin 1992; Pretzsch 1995; Metz et al. 2013) using other or additional metrics may have resulted in enhanced explanatory power for predicting the influence of local competition intensity on quality-related external stem attributes. However, detailed tree crown information was unavailable in our study for either the target tree or the competitors.

Thirdly, our study did not take into account other factors that may affect stem quality such as genetics and soil and climate conditions. However, we assume that growth conditions of the sample trees were similar as all trees grew in the same forest community (see Table 2.1).

Lastly, we are aware that the temporal disjunction between the current competition and the cumulative legacy measures of *number of bark anomalies per metre* and *stem non-circularity (mean)* may impair the strength of our approach. However, beech trees are able to respond quickly enough to changing environmental situations (Pretzsch and Schütze 2005; Pretzsch 2014; Hajek et al.

2015), here competition, to enable relationships for a given point in time to be measured. For this reason, the current external timber quality, which is also a result of past competitive pressure, can be partially explained by the competition levels that the trees were exposed to at the time of the study.

The major analytical advancement presented in our study is the objective and quantitative nature of the approach. To date, *in-situ* quality assessment has been mostly based on a subjective visual inspection. Moreover, it becomes more difficult with increasing height of the stem section to be graded visually. The method presented provides a sound framework for a quality assessment of standing timber based on high-resolution 3D data on the trees for all stem sections.

2.5. Conclusions

This study presents a newly developed approach to assess external timber quality attributes of European beech using TLS. The results showed that TLS is useful to examine external stem characteristics of European beech nondestructively. Thus, our study supports the findings of earlier research that characterised TLS as an objective (Liang et al. 2011) and quantitative method with great potential for nondestructive measurements (Schütt et al. 2004; van Goethem et al. 2008; Kankare et al. 2014; Stängle et al. 2014). Using the newly introduced TLS-based measures *number of bark anomalies per metre* and *stem non-circularity,* we showed that external quality-related stem properties were related to increasing competition, indicating increasing timber value for these trees. Hence, by controlling competition intensity, silvicultural management can improve stem value potential for these trees. Collectively, these results demonstrate the potential utility of the TLS approach in quantifying external stem characteristics in addition to identifying a principal determinant governing their development (local competition intensity). Based on the new approach, our study may further enhance optimisation of stand management towards the production of high-quality timber. The point cloud processing procedure can be applied to mobile laser scanning data, drone-based 3D data from scanning or photogrammetric approaches, and 3D data from other approaches in the same way as shown here for tripod-based data. Hence, it may offer opportunities for future applications that consider more trees, mixed stands, or other target species. In the near future, point clouds from mobile and handheld laser scanning are likely to replace laboriously acquired data from tripod-based laser scanning (as conducted in our study) and thus increase the probability for practical applications of the approach used.

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Chapter 3

Analyzing effects of intra- and interspecific competition on timber quality attributes of *Fagus sylvatica* L. - from quality assessments on standing trees to sawn boards

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3. Second study

Abstract

Timber quality is the main driver of timber prices and is strongly influenced by the competition a tree experiences until its day of harvest. Regulating competition is an integral part of silviculture, and therefore, deeper understanding of the competitor's influence on timber quality is important. Since mixed forest stands and the share of broadleaved tree species have increased in the recent past because of a changed forest policy in several countries, effects of mixture types on timber quality are of increasing importance. In this study, we investigated the effects of intra- and interspecific competition on the internal timber quality of European beech (*Fagus sylvatica* L.). To analyze the effects of competition intensity and competitor species identity on the timber quality of 82 target beech trees, three different approaches were used: terrestrial laser scanning (TLS), a quality assessment on the standing tree by local district foresters, and a quality assessment of the sawn wood (boards) after harvesting. We investigated the relationship between external and internal quality features and additionally compared the different approaches to assess quality. We found that the present competitive situation was partly related to internal timber quality, with increasing competition leading to increased internal timber quality. We further observed more discoloration in timber of beech trees growing in mixture with other broadleaved tree species. We also showed that predicting discoloration is possible through the number of bark anomalies on the stem surface. Also, the external quality assessment of local foresters on standing trees predicted the internal timber features well. Finally, TLS appeared to be a valuable addition for assessing timber quality *in-situ*.

Keywords Discoloration · European beech · Knottiness · Mixed forest stands · Terrestrial laser scanning · Wood quality

3.1. Introduction

In many European countries, the proportion of broadleaved trees in forests and the amount of mixed forest stands in general have increased due to great efforts for converting conifer monocultures into mixed stands in recent decades (von Lüpke et al. 2004; BMEL 2014; Bravo-Oviedo et al. 2014; Forest Europe 2015). The lower proportion of coniferous trees and the continuously high demand for softwood by the timber industry are expected to result in a shortage of softwood (Spellmann 2005; BMELV 2011). Since the amount of hardwoods on the market has increased, information on timber assortments of standing hardwood trees and how these assortments and qualities are influenced by different forest mixture types appear important to counteract the predicted shortage.

Mixed forest stands have been found to differ from pure stands in growth performance (e.g., Pretzsch and Schütze 2009; Pretzsch et al. 2010; Metz et al. 2013; Pretzsch et al. 2015), average tree shape (e.g., Pretzsch and Schütze 2005; Dieler and Pretzsch 2013; Juchheim et al. 2017), wood density (Zeller et al. 2017), and physiological responses of trees in interspecific neighborhoods such as light use efficiency and drought tolerance (e.g., Forrester 2014; Metz et al. 2016). Much less is known on the effect of tree mixtures on individual timber quality. On the one hand, it is well understood that the timber quality of a single tree is substantially influenced by the degree of competition from neighboring trees and can thus be influenced by applying certain silvicultural treatments (Zingg and Ramp 2003; Höwler et al. 2017). On the other hand, there is still a lack of information on tree species identity effects on timber quality (Benneter et al. 2018). Pretzsch and Rais (2016) found a decrease in timber quality (e.g., reduced strength and stiffness, increased branch diameter and length, or increased crown eccentricity and reaction wood) in complex mixed forest stands compared to homogeneous pure forest stands, while Benneter et al. (2018) stated that mixed forest stands can either be favorable or detrimental to stem quality in dependence of, e.g., growth potential, crown plasticity, or shade tolerance of a species. Against this background, further information on effects of mixture type, neighborhood, and neighborhood species identity on timber quality are missing but are urgently needed by forest managers and the wood processing industry for improving felling plans (using tree and stand information) and predicting marketable timber quantity (Wiegard et al. 1997; Stepien et al. 1998; Knoke et al. 2006).

In Central Europe, forest conversion has focused on the enrichment of conifer stands with mostly European beech (*Fagus sylvatica* L.) (Ammer et al. 2008; Rumpf and Petersen 2008), a tree species which would likely dominate forests across Central Europe under natural conditions (Ellenberg and Leuschner 2010). In Germany, European beech is by far the most important broadleaved tree species (Hecht et al. 2015), covering about 1.7 Mio. hectares of forest land (BMEL 2014) and accounting for approximately 21.1 % of the total wood harvest (BMEL 2017). For solid wood furniture production, European beech is one of the most important species due to its high strength and stiffness and its relatively good glueability (Aicher and Ohnesorge 2011).

Timber quality is *inter alia* influenced by site conditions, competition intensity and hence light availability, genetics, damages, and disturbances (Zingg and Ramp 2003; van Leeuwen et al. 2011; Richter 2015; Merganič et al. 2016). Some of these aspects can be controlled silviculturally, that is by directing tree growth and timber quality (Gartner 2005; Ammer 2008; van Leeuwen et al. 2011; Richter 2015; Bartsch and Röhrig 2016). More specifically, diameter at breast height (DBH), size and abundance of knots, crown development, taper, stem curvature, wood density, and the proportion of juvenile wood are important characteristics of timber quality that are also influenced by silvicultural treatments (Hein 2008; van Leeuwen et al. 2011; Richter 2015). Among those, DBH and knottiness are the most important quality characteristics since they strongly influence the achievable price for the timber (Ammer 2016). Higher competition leads to more effective self-pruning and fewer and thinner branches (Ballard and Long 1988; Mäkinen 1999; 2002; Mäkinen and Hein 2006; Hein 2008) but also impedes secondary growth (Ammer et al. 2005). In terms of timber quality, branches lead to knots within the wood. Knots, however, reduce strength and stiffness, affect swelling and shrinkage, as well as the visual appearance of wood products due to deviations and discontinuities in the anatomical structure (Barbour and Parry 2001; Richter 2015; Osborne and Maguire 2016). Especially strength and stiffness or warp are important attributes for construction wood (Gartner 2005; Skog et al. 2015), while appearance is the main factor in veneer (Skog et al. 2015) or furniture wood. Secondary growth influences annual ring width, wood density, the proportions of sapwood, heartwood, juvenile, and mature wood, and the fiber length (van Leeuwen et al. 2011). Hence, knots and tree diameter are influential characteristics for the wood processing industry and also for many end-consumers.

Certain timber quality attributes can be objectively measured and described (Knoke et al. 2006), and various nondestructive methods exist to assess information on timber quality and timber properties of trees, logs, or composites: e.g., computer tomography, thermal imaging, microwave imaging, ultrasonic imaging, nuclear magnetic resonance, neutron imaging, or terrestrial laser scanning (TLS) (Bucur and Timell 2003; Dassot et al. 2011; Höwler et al. 2017). In everyday practice, however, timber quality is usually assessed visually by the local forester or the procurement agent. Apart from the visual assessment by trained personnel, TLS can be considered to be of practical applicability and relevance in the field currently because it offers the possibility to assess numerous tree and quality attributes with relatively little effort.

In order to predict the value of a forest, the marketable timber quantity, timber assortments, and also achievable timber prices, a quality assessment might be a valuable addition to forest inventories. For that, information on the relationship between external and internal timber quality is urgently needed (Sterba et al. 2006).

Here, we investigated to what extent sawn timber quality of European beech is influenced by (1) the degree of competition, (2) different mixture types in terms of neighboring tree species identity, and (3) whether or not and to what degree TLS-derived quality measures and a quality assessment from local district foresters on a standing tree are related to sawn timber quality. We tested the following hypotheses: (1) internal timber quality of European beech trees increases with increasing competition intensity, (2) internal timber quality of European beech trees differs depending on neighboring species identity, (3) externally visible timber quality features are correlated with internal timber quality features, and (4) TLS as well as the quality assessment by the local district foresters can predict internal timber quality of European beech trees.

3.2. Materials and methods

For this investigation, 82 dominant and vigorous European beech trees (see Table 3.1 for sample tree description) belonging to four different mixture types were selected:

1. pure beech stands, *n* (number of selected sample trees) = 25,
2. mixed stands of beech and Norway spruce (*Picea abies* (L.) H. Karst.), *n* = 24,
3. mixed stands of beech and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), *n* = 23, and
4. mixed stands of beech and other broadleaved tree species such as Norway maple (*Acer platanoides* L.), sycamore maple (*Acer pseudoplatanus* L.), or European ash (*Fraxinus excelsior* L.), *n* = 10.

Table 3.1 Description of the 82 selected sample trees with median diameter at breast height (DBH) ± standard deviation (sd), median height ± sd, and age range with minimum (min.) and maximum (max.) age for the four different mixture types pure beech stands (PB), mixed beech stands with Norway spruce (MBN), mixed beech stands with Douglas-fir (MBD), and mixed beech stands with other broadleaved tree species (ash and maple) (MBB). Further details on stand description can be found in Höwler et al. (2017).

		Unit	PB	MBN	MBD	MBB
DBH	**Median**	cm	41.1	42.6	37.7	51.2
	SD	cm	4.4	6.1	6.9	7.4
Height	**Median**	m	30.4	30.2	29.8	34.3
	SD	m	1.6	3.1	2.9	1.9
Age	**Min.**	-	72	72	53	73
	Max.	-	93	90	90	111

All sample trees were selected from the interior parts of the stands with the aim of avoiding edge effects caused by, e.g., roads, trails, and gaps. All stands were growing on rather nutrient-rich and well-drained soils on Triassic sandstone or limestone covered with loess. Selected sample trees from mixed stands had at least two main competitors of the admixed tree species that were also dominant trees (similar DBH and height). All neighboring trees with a DBH ≥ 7 cm within 15 m distance to the stem base of each sample tree were measured (DBH, height, crown base height, and distance to sample tree) using field map (IFER - Monitoring and Mapping Solutions, Ltd., Czech Republic). From this, present competition intensity was calculated according to Hegyi (1974) (cited in Bachmann 1998) (Eq. 3.1):

$$Hegyi_i = \sum_{j=1}^{n} \frac{DBH_j}{DBH_i * (dist_{ij} + 1)} \quad (3.1)$$

with sample tree (i), competitor tree (j), diameter at breast height (DBH, in cm), and distance between sample tree and competitor tree (dist, in m). The competition indices of Hegyi (1974), Biging and Dobbertin (1992), and Pretzsch (1995) were described as most effective to assess competition intensity (Bachmann 1998). However, the indices suggested by Biging and Dobbertin (1992) and Pretzsch (1995) require information about the crown cross-sectional area which was unavailable for the trees used within this study. Therefore, Hegyi's index was chosen for this study to quantify competition intensity.

We tested different competition radii (5, 7.5, 10, 12.5, and 15 m) for competitor inclusion, in order to distinguish between different degrees of competition (see Hartmann et al. 2009). Further information on the selection of the sample trees and a description of the different forest stands can be found in Höwler et al. (2017). The sample trees were harvested in winter 2015/2016 during a commercial felling procedure (late thinning) of the forest district Reinhausen (Niedersächsische Landesforsten, Germany). Prior to harvesting, a quality assessment according to German guidelines (RVR 2014) was conducted for the standing sample trees by local district foresters. The standing sample trees were visually graded and virtually divided into sections (in m) of quality classes B (good quality), C (medium quality), or D (bad quality). No sample tree exhibited quality class A (best quality). In addition to the quality assessment by local district foresters, we used TLS (Faro Focus 3D 120 laser scanner, FARO Technologies 2013, Inc. Lake Mary, Florida, USA) to objectively and quantitatively assess the external timber quality of the sample trees. We performed a multiple-scan approach (van der Zande et al. 2008), with four scans per sample tree and artificial chessboard targets (see Höwler et al. 2017 for details). The xyz files of the sample trees were analyzed using Mathematica (Wolfram Research, Champaign, Illinois, USA) with regard to timber quality, using recently published measures of external stem characteristics (number of bark anomalies, stem non-circularity, lean, and sweep; further details can be found in Höwler et al. 2017). TLS was performed in autumn 2015 in full foliage. Due to high occlusion by leaves, no crown attributes could be acquired from the scans.

After felling, all sample trees were cut into stem sections of 3, 4, or 5 m length (depending on the total length of the tree logs) in a sawmill (Fehrensen GmbH, private limited company, Hann. Münden, Germany). For this study, the first two most important and valuable sections (total lengths of 6, 8, or 10 m, respectively) of the stem for industrial processing (Willmann et al. 2001) were used for further investigation. Since only the upper parts of the sample trees were graded as D-quality, stem sections of this quality class were not part of the analyses. In total, 179 stem sections were sawn into boards using a log band saw (DBH > 70 cm) and a frame saw (DBH < 70 cm). Altogether, 1940 unedged boards of differing thickness (min. 20 mm, max. 50 mm) were sawn. All sections of every sample tree were then piled up to 'rebuild' the tree and to assure an assignment of all boards to the respective section of the sample tree. A single-lens reflex camera mounted on a tripod was used to take three to five images of each board over the entire length of the board (one image covered approximately 1 m along the vertical stem axis, Figure 3.1). A total of 6,186 images were taken. A camera tripod and an attached water-level ensured that each image was taken with the same distance (1 m) and the same angle (90 °) to the board surface. A measuring tape placed besides the surface of the boards allowed for true-to-scale measurements of internal timber quality features. Offcuts were excluded from this study.

Figure 3.1 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).

Using the software CorelDRAW© X4 (version 14.0.0.567, Corel Corporation 2008), all images of each individual board were manually knit together (Figure 3.2; Appendix, Figure 3.8) with a resolution of 600 dots per inch (dpi). The composite images were used for further quality analyses using Datinf® Measure (version 2.2, Datinf GmbH, Tübingen, Germany). First, a scale was put onto the measuring tape at the bottom of each image and verified with the measured total length of the board (using Datinf® Measure) as well as the length of the respective stem section: if the measured total length of a board matched the length of the stem section (e.g., measured total board length equaled 298 cm using Datinf® Measure and matched the 3 m length of the stem section), further measurements were conducted. This scale enabled a transformation from pixels into metric units. Accordingly, the total length of each board and its width (excluding the bark, measured every 50 cm, Figure 3.3) were assessed using the 'distance' tool of the software.

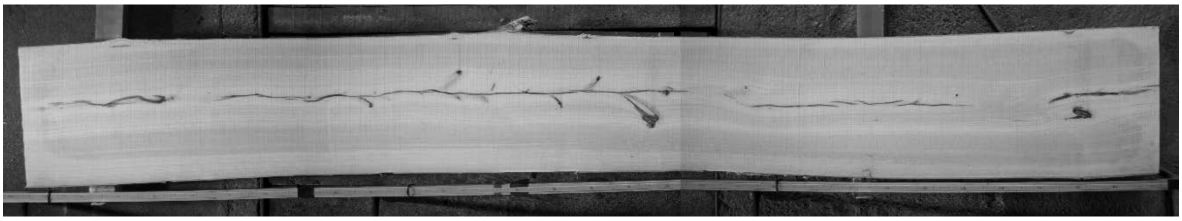

Figure 3.2 Composition of three single images to one image (created using Adobe Photoshop CS3 Extended version 10.0).

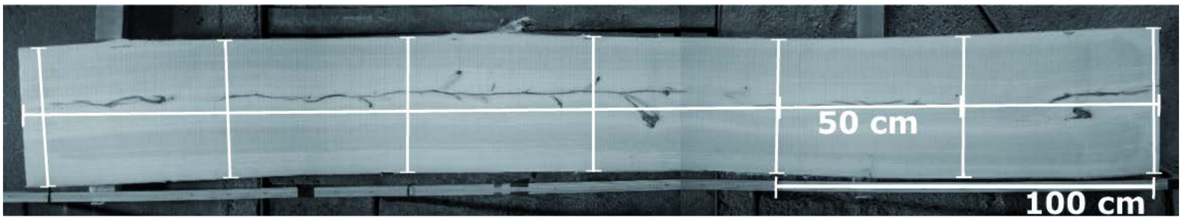

Figure 3.3 Exemplary measurement of the total length and the widths of one board measured every 50 cm. The scale equaled 100 cm (created using INKSCAPE version 0.92 and Adobe Photoshop CS3 Extended version 10.0).

The surfaces of the quality attributes (1) knots and (2) discolorations were measured using the 'polygon' tool. The widths of all knots were determined using the 'rectangle' or 'square' tool. The widths of the discolorations were measured at the point of maximum extent for each image. The position on the measuring tape was assigned to all measured quality attributes in order to evaluate their distribution along the boards of a stem section. Thus, the height of a quality attribute above the forest floor was calculated. Finally, the total area of each board was determined using the 'polygon' tool covering the whole board surface (excluding bark). All measurements were carried out manually, because an automated measurement was not feasible due to different light conditions at the sawmill during image acquisition. Furthermore, the contrasts between the quality features and the remaining wood did not allow an automated operation.

3.2.1. Data processing

For commercial purposes, the stems were cut into sections of different lengths (3, 4, or 5 m, compare above) during the sawing procedure. For our analysis, we decided to use the maximum common board length of all sawn boards (5.65 m) in order to receive comparable objects and a comparable distribution of quality attributes.

The software 'Access' (Microsoft® Access® 2013) was used to extract the quality measurements of the lowermost 5.65 m of each sample tree for the attributes (1) mean board surface area per tree, (2) mean discoloration surface per tree, and (3) mean knot surface per tree. We focused on these quality features because discoloration is the most important quality variable with regard to the buyer's preferences for beech wood (Knoke et al. 2006) and knots on the sawn wood surface are the main drivers of clear wood content in sawn wood, determining the yield (Stängle et al. 2015). We used the arithmetic mean of the quality attributes per sample tree to avoid pseudo replication due to a repeated occurrence of the same quality attribute in several boards. Since the boards varied in thickness, relative values were calculated. All quality attributes were related to the mean board surface area per sample tree (up to 5.65 m height) resulting in the quality metrics *mean discoloration surface* (MCS) and *mean knot surface* (MKS).

3.2.2. Statistical analysis

All statistical calculations were performed using the free software environment R (version 3.4.4, R Core Team 2018). First, the Shapiro–Wilk test was applied to test for normal distribution. If a normal distribution could not be assumed, the Fligner–Killeen test for non-normally distributed data was used to test for homogeneity of variance. Furthermore, Spearman's rank correlation coefficient for non-normally distributed data was calculated and tested for significant relationships between the response variables (y) *mean discoloration surface* and *mean knot surface* (internal timber quality attributes) and the explanatory variables (x) mixture type, competition intensity (Hegyi-index), as well as lean, sweep, stem non-circularity, and number of bark anomalies (external timber quality attributes resulting from the TLS approach). Additionally, Spearman's rank correlation coefficient was used to test for relationships between the external quality assessment on the standing tree and the measured internal timber quality attributes (*mean discoloration surface* and *mean knot surface*).

The nonparametric Kruskal–Wallis test was used to analyze differences in timber quality attributes within the four mixture types followed by a post hoc test of multiple comparisons according to Dunn with Bonferroni correction (R packages 'PMCMRplus', Pohlert 2018).

Since the assumptions for parametric testing were violated, we used nonparametric generalized additive models (GAM) to describe the relationship of competition intensity and mixture type on the measured quality attributes *mean discoloration surface* and *mean knot surface*. GAMs were chosen since no specifications on data distribution are required prior to testing (Crawley 2011; Annighöfer 2018), and thus, an unbiased overview of the general tendencies within the data was enabled. The data family was set to 'Gaussian' with an 'identity-link function', and, in dependency of the sample or subsample size, the number of knots was set to a maximum of 5 (non-species-specific GAMs; sample) or 3 (species-specific GAMs; subsample) with automated adaption via generalized cross-validation to avoid the effect of over-fitting and to enable a reliable interpretation of the results (Dormann and Kühn 2012).

All statistical tests were performed for a competition radius encompassing 10 m, because a 10 m radius equaled the median radius. Additional tests were performed for comparing other competition radii (5, 7.5, 12.5, and 15 m) and competition intensities. Unless otherwise noted, results refer to a competition radius of 10 m.

No crown attributes could be acquired from the terrestrial laser scans due to high occlusion by leaves. In order to still include species-specific information, crown widths for the competitor and sample trees were estimated using tree species, DBH, and tree height as input variables for the R package 'anstaltspaket' (Nuske 2017). The significance level $p < 0.05$ was chosen for all statistical tests conducted in this study.

3.3. Results

3.3.1. Competition intensity (Hegyi-index) and internal timber quality

Spearman's rank correlation revealed that present competition intensity (Hegyi-index) was not significantly correlated to *mean knot surface* ($p = 0.689$, rho = − 0.043), a measure of knottiness. However, a significant negative correlation was observed between competition intensity and *mean discoloration surface* ($p = 0.011$, rho = − 0.269), a measure of deviation from the desired timber color.

Generalized additive modeling (GAM) confirmed this significant negative relationship between the quality attribute *mean discoloration surface* and competition intensity (Figure 3.4a). The GAM explained 8.22 % of the deviance and the adjusted R^2 equaled 0.06 (Appendix, Table 3.5). Hegyi values > 1.5 resulted in *mean discoloration surface* < 10 % (Figure 3.4a). In contrast, no significant relationship between the quality attribute *mean knot surface* and competition intensity was found (Figure 3.4b). Only 4.61 % of the deviance in *mean knot surface* was explained by competition intensity (Figure 3.4b; Appendix, Table 3.5). On the other hand, as for *mean discoloration surface*, *mean knot surface* values did not exceed 0.10 % with Hegyi-indices > 1.5 (Figure 3.4b).

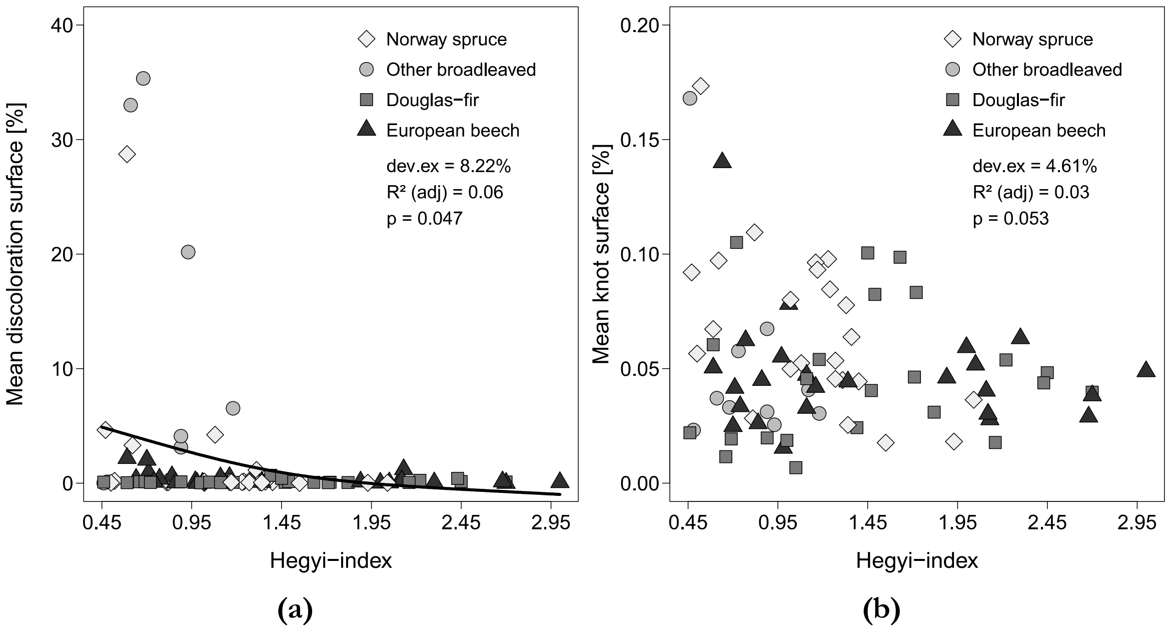

Figure 3.4 Relationship between competition intensity (Hegyi-index) on the sample trees ($n = 82$) and the quality attributes **(a)** *mean discoloration surface* (MCS) and **(b)** *mean knot surface* (MKS) per sample tree for the lowermost 5.65 m of the stem using generalized additive models (GAMs) (significant relationships at $p < 0.05$ are shown using a solid black line; smoothing term = Hegyi-index; with dev.exp = deviance explained, R^2 (adj.) = adjusted R^2, and corresponding p value of the smoothing term).

3.3.2. Effect of neighborhood species identity on the internal timber quality

The distribution of the quality attributes *mean discoloration surface* and *mean knot surface* was fairly equal within each mixture type (spruce, other broadleaved tree species (OB), Douglas-fir, and beech) (Figure 3.5; Table 3.2).

Table 3.2 Maximum (max.) and minimum (min.) values as well as standard deviation (SD) for the two quality attributes *mean knot surface* (MKS) and *mean discoloration surface* (MCS) for the four different mixture types pure beech stands (PB), mixed beech stands with Norway spruce (MBN), mixed beech stands with Douglas-fir (MBD), and mixed beech stands with other broadleaved tree species (ash and maple) (MBB).

	MKS [%]			**MCS [%]**		
	Max.	**Min.**	**SD**	**Max.**	**Min.**	**SD**
PB	0.140	0.015	± 0.024	2.177	0.008	± 0.589
MBN	0.173	0.018	± 0.036	28.730	0.019	± 5.889
MBD	0.105	0.007	± 0.030	0.678	0.037	± 0.157
MBB	0.168	0.023	± 0.043	35.335	0.012	± 13.961

The only significant difference between the four mixture types was found for European beech trees in mixture with other broadleaved tree species (ash and maple) for the quality attribute *mean discoloration surface*. Sample trees surrounded by ash and maple had a significantly higher *mean discoloration surface* (median = 3.62 ± 13.96 % SD; Figure 3.5a; Table 3.2; Appendix, Figure 3.8).

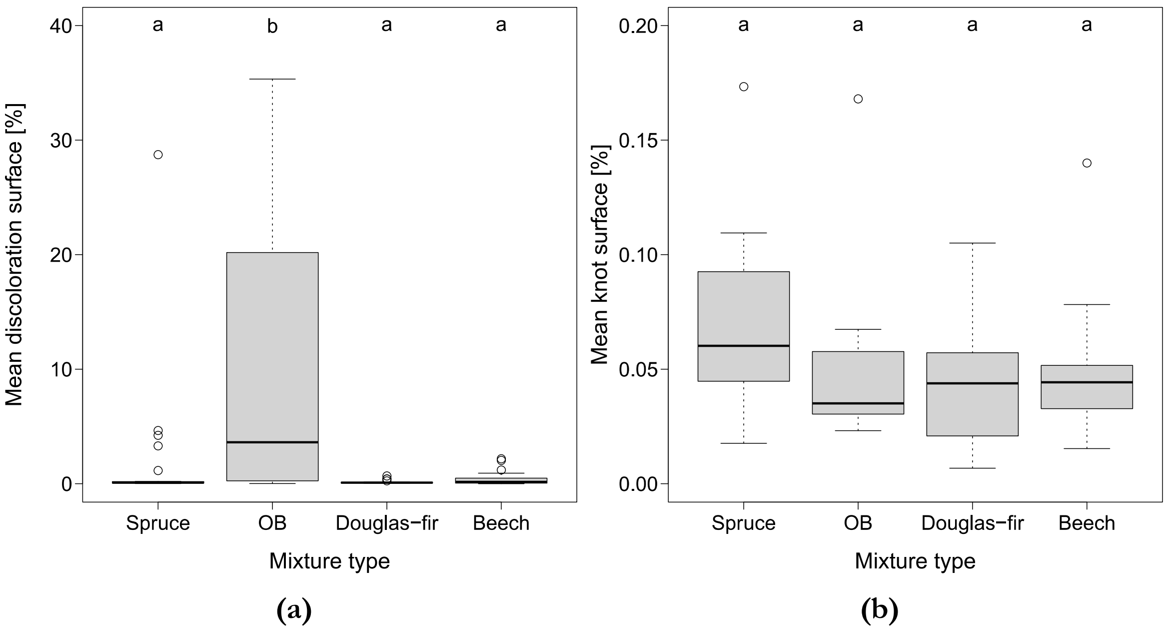

Figure 3.5 Range of the internal timber quality attributes **(a)** *mean discoloration surface* (MCS) and **(b)** *mean knot surface* (MKS) per sample tree for all 82 sample trees within each mixture type (spruce ($n = 24$), other broadleaved tree species (OB) ($n = 10$), Douglas-fir ($n = 23$), and beech ($n = 25$)). Letters (a and b) indicate significant differences between the mixture types at $p < 0.05$ (nonparametric, Kruskal–Wallis test).

The species-specific GAMs, describing the relationship between competition intensity (Hegyi-index) and the quality attributes within the four different mixture types, revealed a significant negative relationship between *mean knot surface* and competition intensity for sample trees in mixture with spruce, explaining 32.7 % of the deviance in *mean knot surface* (Figure 3.6a). Still, *mean knot surface* values of the sample trees did not exceed 0.05 % under highest competition (max. Hegyi-index) for all four mixture types (Figure 3.6). We did not find any significant relationship for intra- and interspecific competition intensity and *mean discoloration surface* (data not shown).

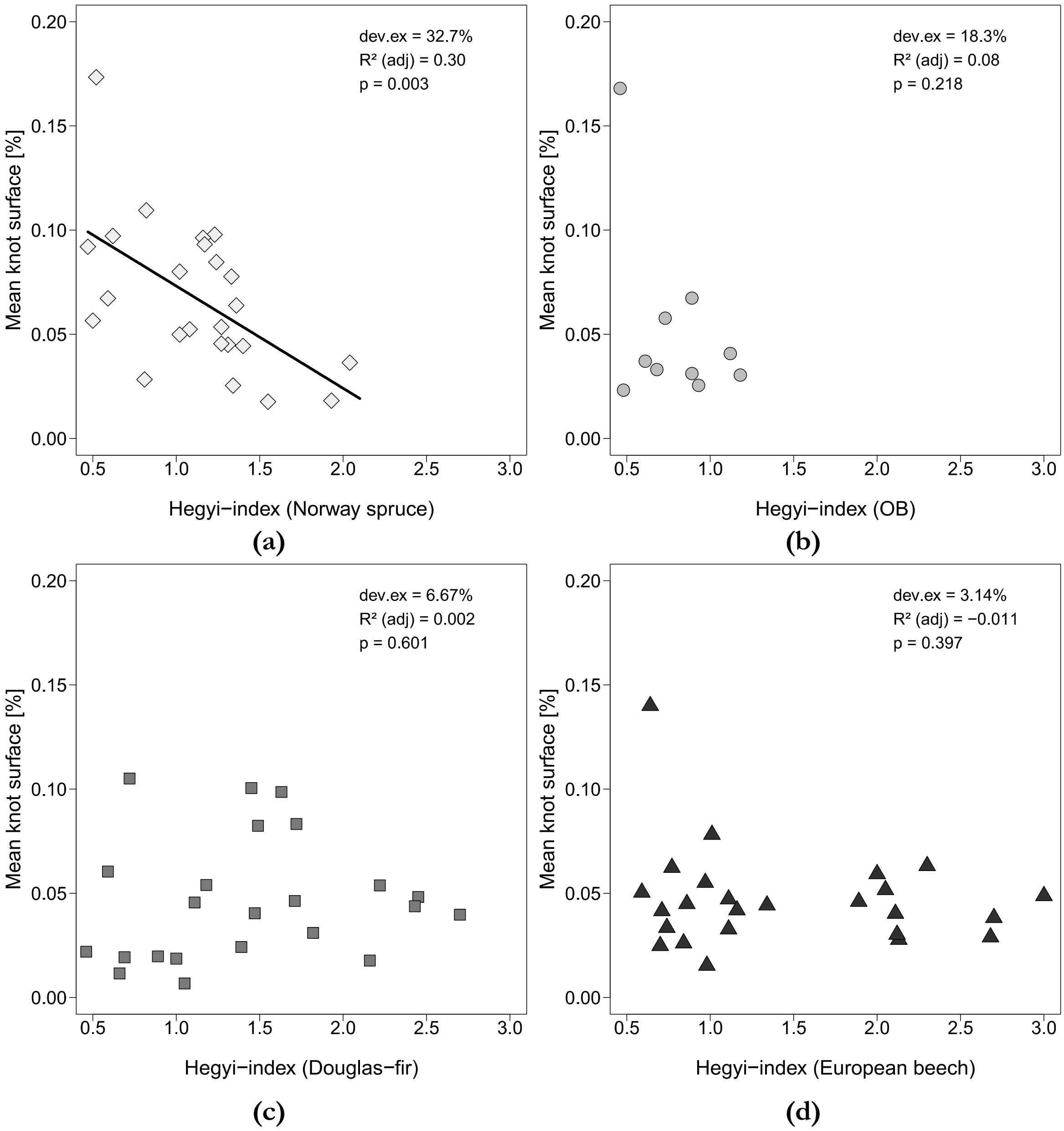

Figure 3.6 Results of the generalized additive models (GAMs) showing the relationship between competition intensity (Hegyi-index) per mixture type [**(a)** Norway spruce (n = 24), **(b)** other broadleaved tree species (OB) (n = 10), **(c)** Douglas-fir (n = 23), and **(d)** European beech (n = 25)] and the quality attribute *mean knot surface* (MKS) (significant relationships at $p < 0.05$ are shown using a solid black line; smoothing term = Hegyi-index per mixture type; with dev.exp = deviance explained, R^2(adj.) = adjusted R^2, and corresponding p value of the smoothing term).

3.3.3. Quality assessment on the standing tree and internal timber quality

There was a significantly negative correlation between the *mean knot surface* as an internal timber attribute and the amount of tree sections graded in quality class B as assessed by the local foresters. In other words, the higher the amount of tree sections of quality class B, the lower the *mean knot surface*. In addition, *mean discoloration surface* increased with an increasing amount of tree sections graded as quality class C (Table 3.3).

The only significant correlation between the TLS-based measure number of bark anomalies (for the lowermost 5.65 m of the stem) was revealed for *mean discoloration surface*: *mean discoloration surface* increased with an increasing number of bark anomalies (Table 3.3). We did not find significant correlations between *mean discoloration surface* or *mean knot surface* and the TLS-based measures lean and sweep (Table 3.3).

Table 3.3 Spearman's rank correlation (ρ) and corresponding p values for the two internal timber quality attributes *mean discoloration surface* (MCS) and *mean knot surface* (MKS) for the lowermost 5.65 m of all sample trees ($n = 82$) and the quality assessment on the standing tree by the local district foresters (assigning the sample trees to either quality class B (QCB) or quality class C (QCC), in meter) and terrestrial laser scanning (assessing number of bark anomalies (BA), mean stem non-circularity (SNC), lean (L), and sweep (S)).

	MCS		**MKS**	
	p **value**	ρ	p **value**	ρ
QCB	0.475	-0.080	0.048	-0.219
QCC	0.002	0.345	0.173	0.152
BA	0.021	0.255	0.950	-0.007
SNC	0.477	0.080	0.974	0.046
L	0.594	-0.060	0.232	0.227
S	0.655	-0.050	0.095	0.310

Applying GAMs revealed that 62.5 % of the deviance in *mean discoloration surface* was explained by the amount of quality class C, and 10.7 % was explained by the number of bark anomalies (Appendix, Table 3.5). Further significant relationships were found between *mean knot surface* and the TLS-based measures mean stem non-circularity and sweep (Appendix, Table 3.5) showing higher *mean knot surface* with increased mean stem non-circularity and increased sweep.

Species-specific GAMs revealed significant relationships between the number of bark anomalies and *mean discoloration surface* for sample trees that had grown in mixture with spruce or in conspecific neighborhoods (Figure 3.7a, d). *Mean discoloration surface* increased with an increase in number of bark anomalies. No significant relationship was observed for sample trees in mixture with other broadleaved tree species or Douglas-fir (Figure 3.7b, c).

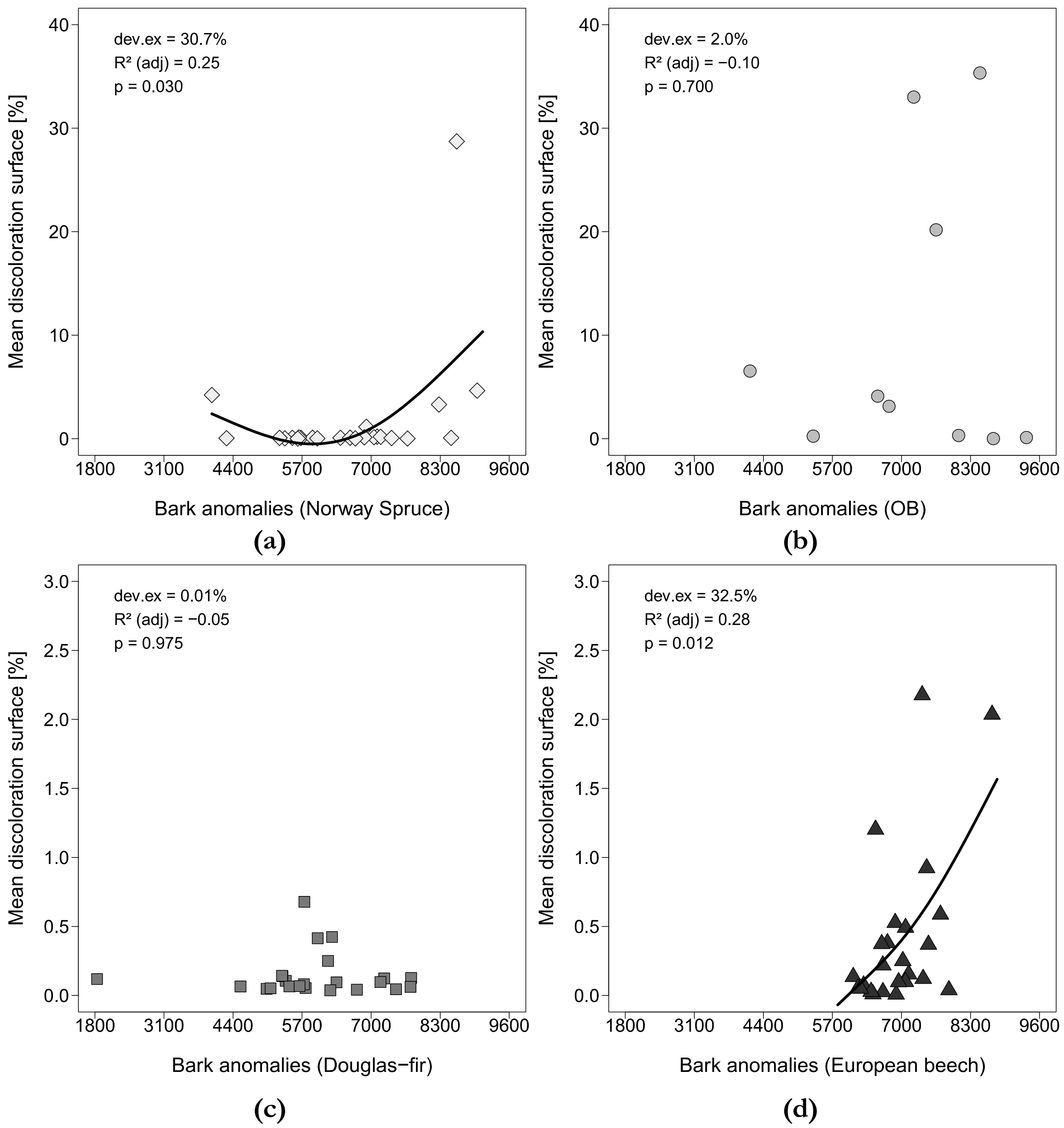

Figure 3.7 Results of the species-specific generalized additive models (GAMs) describing the relationship between the number of bark anomalies (BA) per sample tree and the quality attribute *mean discoloration surface* (MCS) for the beech sample trees in four different mixture types [**(a)** Norway spruce ($n = 24$), **(b)** other broadleaved tree species (OB) ($n = 10$), **(c)** Douglas-fir ($n = 23$), and **(d)** European beech ($n = 25$)]. Ordinate was adjusted to a maximum of MCS = 3.0 % for the mixture types Douglas-fir and European beech (significant relationships at $p < 0.05$ are shown using a solid black line; smoothing term = number of bark anomalies per sample tree and per mixture type; with dev.exp = deviance explained, R^2 (adj.) = adjusted R^2, and corresponding p value of the smoothing term).

3.3.4. Additional effects on internal timber quality

The quality attribute *mean discoloration surface* was significantly and positively correlated to DBH, age, height, and mean board surface area (BSA, Table 3.4). *Mean knot surface* was significantly negatively correlated to age only.

Table 3.4 Spearman's rank correlation (ρ) and corresponding *p* values for the two internal timber quality attributes *mean discoloration surface* (MCS) and *mean knot surface* (MKS) for the lowermost 5.65 m of all sample trees and the sample tree attributes DBH, height (*h*), age, and mean board surface area (BSA).

	MCS				MKS			
	DBH	**BSA**	**Age**	**H**	**DBH**	**BSA**	**Age**	**H**
***p* value**	< 0.001	< 0.001	< 0.001	< 0.001	0.79	0.90	< 0.05	0.19
ρ	0.39	0.47	0.41	0.49	-0.03	-0.01	-0.21	-0.14

Additionally, the quality attribute *mean discoloration surface* increased ($p = 0.015$, rho = 0.26) and *mean knot surface* decreased ($p = 0.018$, rho = − 0.25) with increasing calculated median crown width of the nearest and greatest competitor trees (DBH ≥ 30 cm, mean distance to target tree = 6.67 ± 1.88 m).

3.4. Discussion

3.4.1. Influence of competition intensity on timber quality

Timber quality is known to be substantially influenced by the degree of competition from neighboring trees (Zingg and Ramp 2003; Höwler et al. 2017). Initial spacing, stand development, and crown architecture determine timber quality of trees because of growing space availability, light availability, or shading, and the ability to compete with neighboring trees (Barbeito et al. 2014). More growing space through wide initial spacing is related to higher light availability, and commonly leads to greater crown dimensions resulting in increased diameter and volume increment as well as shorter rotation cycles (e.g., Mäkinen and Hein 2006; Bartsch and Röhrig 2016; Pretzsch and Rais 2016). However, more growing space, higher light availability, and greater crown dimensions also lead to thicker branches, increased tree ring width, more excessive stem taper, or slenderness, and consequently reduced external and internal timber quality (e.g., Mäkinen 2002; Mäkinen and Hein 2006; Richter 2015; Pretzsch and Rais 2016). Thus, present timber quality can be considerably influenced by former silvicultural management, if applied to control competition or to reduce branchiness by pruning. Against this background, it is not surprising that the present competitive situation could only partly explain timber quality of the sample trees, since the present appearance of a tree is a result of its growth history. Knowledge about the competitive situation an individual went through during its development and not only about the present stage of competition would be required to improve the explanation strength of competition intensity (Hegyi-index) on timber quality. However, our study could show that even the present competitive situation was related to *mean discoloration surface*. In addition, for high competition intensity (as expressed here using the Hegyi-index) values at present, only low values of both quality attributes, *mean discoloration surface*, and *mean knot surface*, were found. Thus, if the competition between trees is presently still high, *mean knot surfaces* and *mean discoloration surfaces* were always low. These findings suggest that controlling stand density and hence competition pressure are reliable silvicultural tools to positively affect internal hardwood timber quality (Mäkinen and Hein 2006). While low competitive pressure may not necessarily lead to high branchiness, high competitive pressure clearly reduces branchiness, which is related to internal timber quality attributes (Mäkinen and Hein 2006; Hein 2008). Overall, we could confirm our first hypothesis stating that internal timber quality (*mean discoloration surface* and *mean knot surface*) of European beech trees increases with increasing competition intensity (Hegyi-index).

3.4.2. Effect of intra- and interspecific competition

In our second hypothesis, we stated that internal timber quality of European beech trees differs depending on neighboring tree species identity. This hypothesis could only partly be confirmed here. The only significant difference in the range of the quality attributes *mean discoloration surface* and *mean knot surface* within the four different mixture types was observed for sample trees growing in mixture with other broadleaved trees. Beech trees in mixture with ash and maple had significantly higher *mean discoloration surfaces* compared to beech trees growing in the three other mixture types. This finding may, however, be an artifact and could also be explained by the significant relationship between *mean discoloration surface* and age as well as size of the sample trees in mixture with ash and maple. In the mixed stands with ash and maple, the oldest and largest (DBH, height) sample trees were found. Additionally, these trees were exposed to the lowest competition intensity (Hegyi-index) as it is necessary to account for the lower competitiveness in terms of shade tolerance, lateral pressure, and crown plasticity of the admixed tree species (here ash and maple; Nüßlein 1995). Age and the average diameter growth rate are known to be the most important factors influencing the probability of discoloration in European beech (e.g., Knoke and Schulz Wenderoth 2001; Knoke 2003a; Knoke 2003b): the higher the average diameter increment rate, the lower the probability of discoloration in beech trees having the same DBH. Furthermore, the higher the age and/or the diameter, the higher the probability of discoloration, e.g., having either two trees of the same DBH (tree with higher age shows higher probability) or of the same age (tree with higher DBH shows higher probability). This is in line with our finding that the oldest and largest sample trees showed highest *mean discoloration surface*.

Site conditions may also influence the occurrence and size of discoloration in timber of European beech trees. Although frequently mentioned in practical forestry, the soil nutrient status is not unambiguously correlated with discoloration and seems to be less important compared to age and diameter in most cases (e.g., Knoke and Schulz Wenderoth 2001; Wernsdörfer et al. 2005a; Wernsdörfer et al. 2005b). Since all sample trees grew in the same forest community, site conditions were assumed similar and were excluded from this analysis. Therefore, the effect of our study sites and potential site differences on discoloration of beech timber remains unclear. *Mean discoloration surface* was further significantly related to competition intensity (Hegyi-index; high competition intensity led to low *mean discoloration surface*), but the relationship was rather weak. Since this finding exclusively resulted from high discoloration values of the sample trees that grew in the neighborhood of ash and maple, it may not express a general pattern. It is likely that not the mixture type as such, but the higher age and/or greater diameter of the sample trees in mixture with ash and maple caused higher *mean discoloration surfaces*. The same is true for the positive relationship between calculated median crown width and *mean discoloration surface*: here we observed that a higher calculated median crown width of the competitor trees resulted in higher *mean discoloration surface* in the target trees. Ash as well as maple competitor trees had the widest calculated crowns. Note that we only analyzed the lowermost 5.65 m of the sample trees stems. Hecht et al. (2015) and Knoke (2003b) demonstrated that damages in the upper part of the tree as well as the occurrence of stem forks increase the risk of discolorations and it is likely that this phenomenon is more abundant in stem sections not considered here (> 5.65 m).

Most interestingly, the *mean knot surface* area did not exceed values of 0.05 % at highest competitive pressure. This underlines that beech trees exposed to high competition pressure exhibit reduced branchiness (Hein 2008) and that low branchiness corresponds to increased internal timber quality. Beech trees growing in the surrounding of Norway spruce had a lower *mean knot surface* with increasing competition intensity even over the whole range of Hegyi-index. Nevertheless, it is possible that our approach was unable to capture certain competition mechanisms such as light availability and light transmission to disentangle species effects for all admixed tree species because these effects could be related to tree attributes that are independent from their competitive effect measured using Hegyi's index. For example, noble hardwood species need wider crowns to keep up in diameter growth when competing with European beech (Nüßlein 1995). Both DBH and distance to the neighbors determine the Hegyi-index, and highest values of both, DBH and distance, were found in mixture with noble hardwood species. Other species such as Douglas-fir and Norway spruce could have overtopped beech sample trees (Bartelink 2000; Pretzsch and Schütze 2009), not accounted for by the Hegyi-index, since the Hegyi-index only reflects some aspects of competition (DBH and distance) but does not account for species-specific attributes, such as height, crown dimensions and form, or light transmission. In other words, neighboring trees of different species, but same dimension and distance, can result in the same Hegyi-index, while exposing a target tree to very different levels of competition in reality (e.g., in terms of different light conditions). Hegyi's index might therefore only be of limited expressiveness.

3.4.3. Relation between external and internal timber quality attributes

In our third hypothesis, we assumed that externally visible timber quality features relate to internal timber quality features. In fact, the external quality attribute number of bark anomalies was related to *mean discoloration surface*. *Mean knot surface*, in contrast, was not predictable from number of bark anomalies assessed by TLS. The quality attribute number of bark anomalies is a measure of irregularities on the stem surface (Höwler et al. 2017), and no differentiation is made regarding the source of these irregularities (e.g., knots, damages, bulges, or notches), their size and shape. Most likely, this lack of differentiation is one reason for the missing relationship between the *mean knot surface* and the number of bark anomalies. A large *mean discoloration surface* area may be attributable to, e.g., larger bark or stem surface damages that resulted in great bark surface irregularities detected by the TLS and consequently a high number of bark anomalies. Larger damages or larger branches have higher occlusion times and increase the possibility of entering oxygen that correspondingly may lead to discoloration (Knoke and Schulz Wenderoth 2001; Wernsdörfer et al. 2005b). TLS-based predictions of discolorations inside the stem therefore seem possible and plausible, but internal knottiness may also be caused by smaller branches not detected with our TLS approach, or that these irregularities date too far back in time to be detected properly by TLS.

Unlike the quality assessment based on TLS, the local foresters were clearly able to make reliable predictions regarding internal timber quality by visual assessment. Among others, this is due to the well-known relationship between the size or length of branch scars on smooth bark surface tree species ('Chinese beards' on European beech) and the corresponding depth of these knots within the stem (e.g., Stängle et al. 2014; Richter 2015). Furthermore, the visual assessment benefitted from the known relationship between the number of injuries on the bark surface and discoloration in European beech trees (e.g., Knoke 2003b). Finally, local foresters were able to identify timber quality characteristics such as spiral grain, wavy fibered growth, corkscrew-log, seams, and knots and rated these stems as C-quality. Here, our results showed that these attributes reflect low internal timber quality in terms of internal knots and discoloration very well. This is in accordance with results by Sterba et al. (2006) who also found significant correlations between a visual external quality assessment and the proportion of sold logs assigned to quality grade B or C, or sold for pulp, paper, and fuel production.

In conclusion, we can confirm our third and fourth hypotheses to a great extent: it can be stated that an experienced person is able to predict the internal timber quality by assessing the overall external quality and that externally visible timber quality features (number of bark anomalies on the stem surface) were correlated with internal timber quality features (*mean discoloration surface*).

3.5. Conclusion

In this study, we investigated the effect of competition intensity (Hegyi-index) and neighborhood species identity on internal timber quality. It was found that competition intensity (present situation) was negatively related with the *mean discoloration surface* and the number of bark anomalies. Furthermore, as expected, high values of *mean discoloration surface* or *mean knot surface* were not found when present competition intensity was high. We can confirm empiric findings that timber quality is influenced by the degree of competition and that regulating competition is an important factor for the quality development of a tree. Still, the identified relationships were rather weak, indicating that the growth history of a forest stand is more important than the present situation in order to thoroughly understand and describe timber quality development.

No clear pattern could be identified for the effect of differing neighbor tree species on the timber quality of sampled beech trees. In conclusion, neighboring tree species identity seemed to have a lesser effect on beech timber quality compared to competition intensity. This finding is in line with the results of a recent study using the same target species, European beech (Benneter et al. 2018).

The externally visible quality features (number of bark anomalies from TLS) correspond to internal quality features such as *mean discoloration surface*. Internal quality was also very well predictable by a quality assessment made by local district foresters.

Although many of our results seem to be reasonable and confirmed by practical experience, others are not as straight forward. For instance, a prediction of knots using TLS was not yet reliably possible. A differentiation between the source, size, and shape of bark anomalies on smooth bark surface tree species by the scanner appears to be very important for an adequate quality assessment but is yet missing and will be the focus of future research. Also, including rough bark surface tree species and sample trees of different age classes (e.g., 10, 30, 50, 70) might be useful to further test the established approach of connecting external bark irregularities with internal knottiness. In addition, in future studies we suggest to increase the sample size to better differentiate between the potentially influencing factors.

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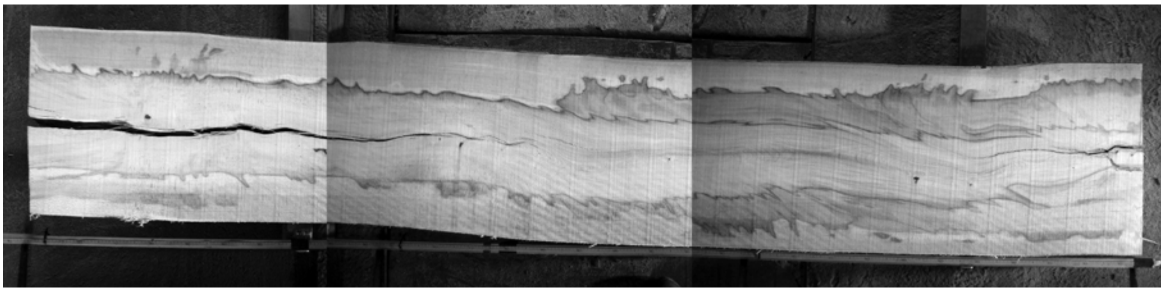
Appendix

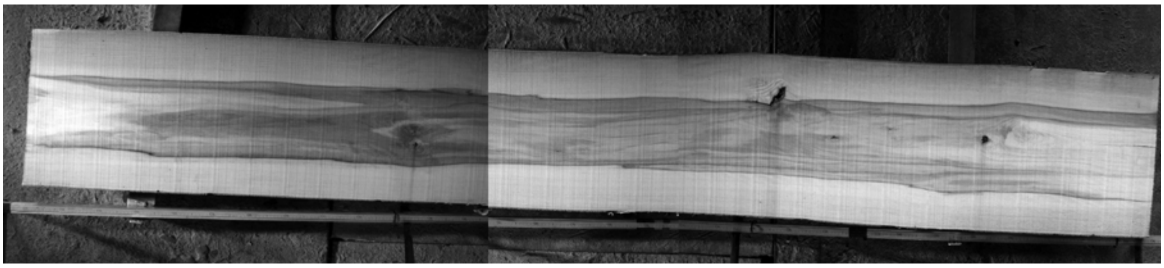
See Table 3.5 and Figures 3.8, 3.9, 3.10, 3.11.

Table 3.5 Summary of the generalized additive model (GAM) with statistical significance (*F* test) of the smoothing term (p_{smooth}), deviance explained by the model (DE), effective degrees of freedom as an indicator for linearity (EDF), and adjusted R^2 (R^2 (adj.)). No differentiation regarding the mixture type, all species included to the model. The number of knots equals 5, and *n* equals 82 (MCS = *mean discoloration surface*, MKS = *mean knot surface*, QCB = quality class B, QCC = quality class C, BA = number of bark anomalies, L = lean, S = sweep, and SNC = mean stem non-circularity).

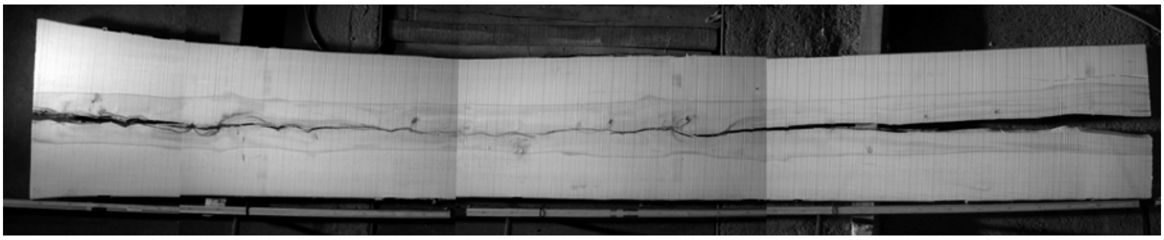
Model	p_{smooth}	**DE (%)**	**EDF**	R^2 **(adj.)**
MCS ~ Hegyi	0.047	8.22	1.57	0.06
MKS ~ Hegyi	0.053	4.61	1	0.03
MCS ~ QCB	0.097	6.54	1.56	0.05
MKS ~ QCB	0.075	3.91	1	0.03
MCS ~ QCC	0.000	62.50	3.71	0.61
MKS ~ QCC	0.122	2.96	1	0.02
MCS ~ BA	0.031	10.70	1.93	0.09
MKS ~ BA	0.259	1.59	1	0.01
MCS ~ L	0.860	0.04	1	-0.01
MKS ~ L	0.209	6.77	2.42	0.04
MCS ~ S	0.477	0.64	1	-0.01
MKS ~ S	0.042	5.08	1	0.04
MCS ~ SNC	0.1	4.24	1.13	0.03
MKS ~ SNC	0.043	12.40	2.85	0.09



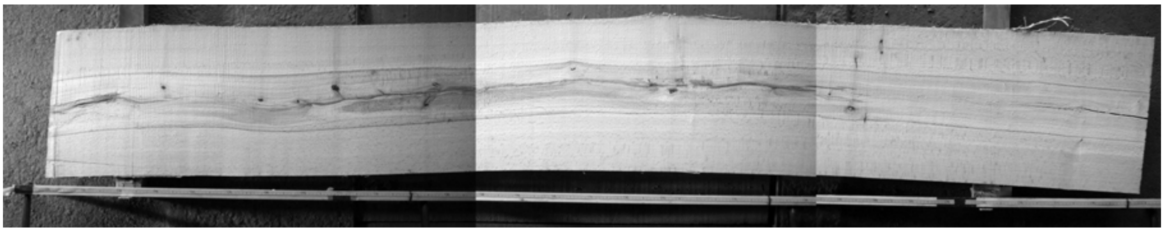
(a)



(b)

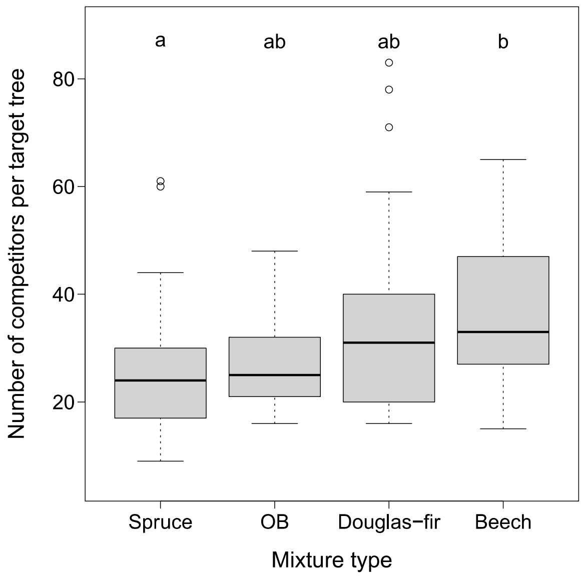


(c)

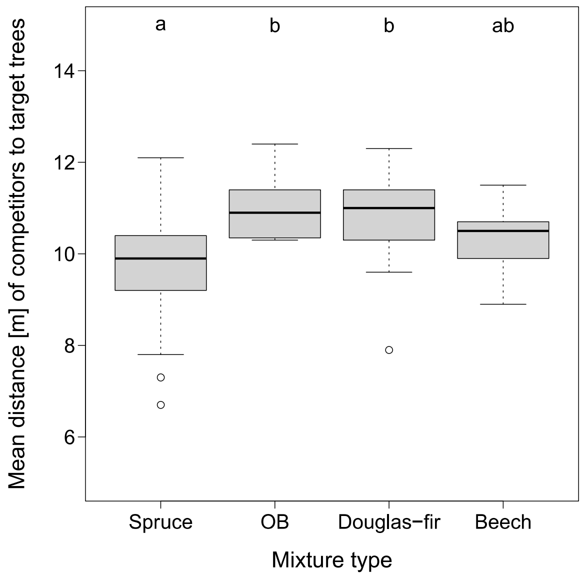


(d)

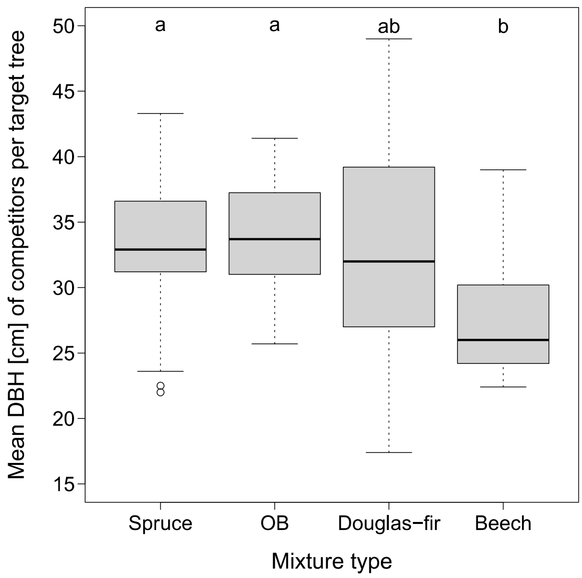
Figure 3.8 Exemplary images of boards from sample trees mixed with other broadleaved tree species (ash and maple) showing highest discoloration surfaces with **(a)** 35.33 %, **(b)** 33.01 %, **(c)** 28.73 %, and **(d)** 20.18 % *mean discoloration surface* per target tree (created using Adobe Photoshop CS3 Extended Version 10.0).



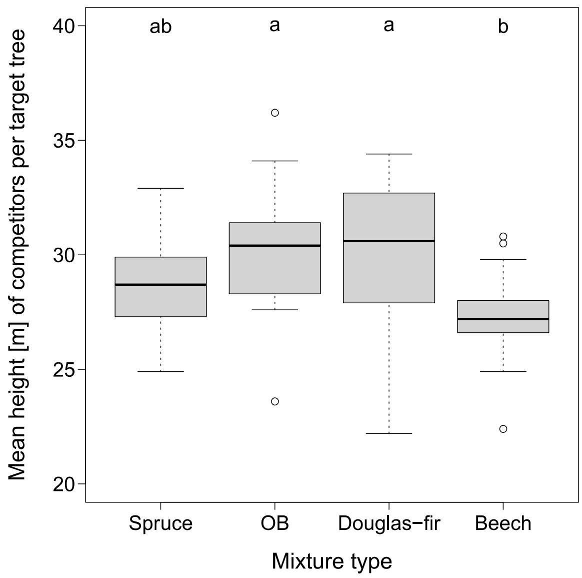
(a)



(b)



(c)



(d)

Figure 3.9 Differences of competitor tree attributes (**(a)** number of competitor trees, **(b)** mean distance [m], **(c)** mean DBH [cm], and **(d)** mean height [m]) per sample tree within the four different mixture types (spruce, other broadleaved tree species (OB), Douglas-fir, and beech). Letters (a and b) indicate significant differences between the mixture types at $p < 0.05$ (nonparametric, Kruskal-Wallis test).

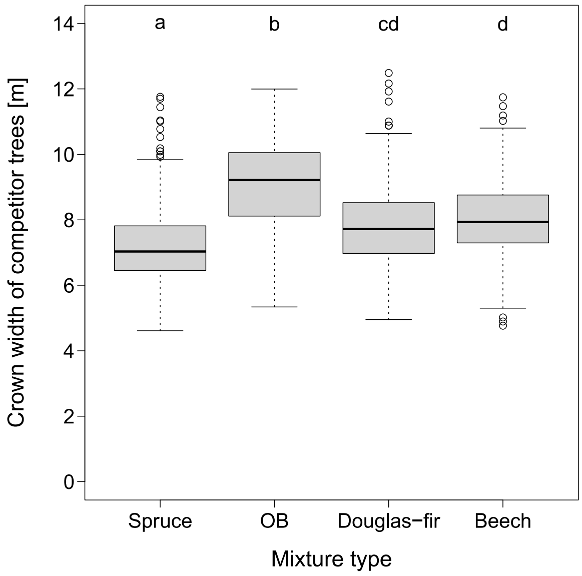


Figure 3.10 Range of the calculated competitor's crown width [m] within each mixture type (spruce, other broadleaved tree species (OB), Douglas-fir, and beech) for all competitor with a DBH ≥ 30 cm. Letters (a, b, c, and d) indicate significant differences between the groups at $p < 0.05$ (nonparametric, Kruskal-Wallis test).

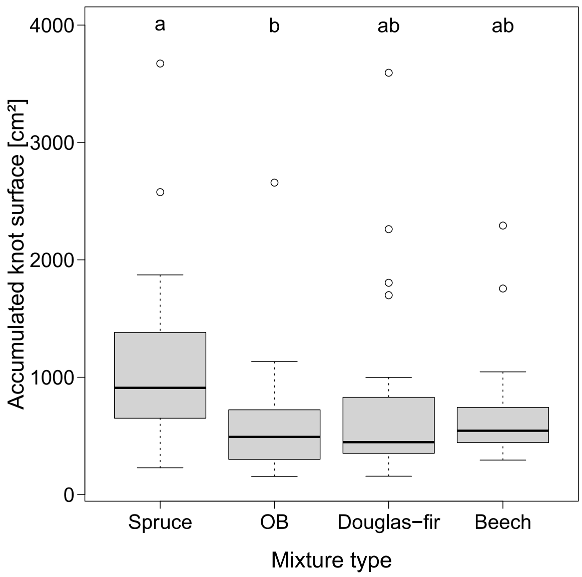


Figure 3.11 Range of the accumulated *knot surface* [cm²] for all sample trees within each mixture type (spruce, other broadleaved tree species (OB), Douglas-fir, and beech). Letters (a and b) indicate significant differences between the mixture types at $p < 0.05$ (nonparametric, Kruskal-Wallis test).

Chapter 4

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

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[*]Kirsten Höwler was responsible for literature and data collection, data analyses, presenting results and writing the manuscript. Torsten Vor, Dominik Seidel, Peter Annighöfer, and Christian Ammer supported the development of a method to process the recorded data and supervised the manuscript and data analyses. Peter Schall assisted the statistical evaluations.

4. Third study

Abstract

Research on mixed forests 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 to 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

4.1. Introduction

Throughout the 20th century, forest management has perfected commercial timber production in forest stands consisting of only one tree species. As a result, even in areas that are naturally rich in tree species, a few species grown in monocultures dominate the picture and working in mixed stands has only recently increased (Willis et al. 2019). This development was based on the great simplicity of even-aged monospecific forests (Bauhus et al. 2017a). This also applies to large parts of Europe, which has a comparatively low number of tree species in global comparison (FAO 2006). However, over the years it has been found that monospecific stands are not only far from what can be found in natural forests (with a few exceptions such as European beech), but that they are more susceptible for abiotic and biotic stressors (Bauhus et al. 2017a). This has led to a movement towards 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). This is due to changes in forest policies which have led to giving priority to regeneration forests with deciduous trees (Lorenz et al. 2018), naturally as well as artificially. In many European countries, pure coniferous forests are converted into mixed and deciduous forests, since mixed forest stands are considered to promote biological and structural diversity (von Lüpke et al. 2004; Knoke et al. 2008; Bauhus et al. 2017a), may 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; Knoke et al. 2008; Knoke and Seifert 2008). Furthermore, recent storm, drought, and heat events caused a direct and significant reduction of coniferous stands (e.g., Schelhaas et al. 2003; Mezei et al. 2017). Additionally, pure deciduous forests are converted into mixed deciduous forests including coniferous species in order to keep an adequate amount of coniferous timber (admixing e.g., *Pseudotsuga menziesii* (Mirb.) Franco, *Picea abies* (L.) H. Karst., *Abies alba* Mill.; e.g., Brosinger and Östreicher 2009; Nabuurs et al. 2014; Stanturf et al. 2014; Rais et al. 2020). However, it is not known whether the mentioned advantages of mixed forests come at the expense of timber quality. Especially 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), mixed neighborhood effects on deciduous timber quality 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 accounted for about 80 % and wood fuel 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). According to Jochem et al. (2015) the proportions of utilized coniferous and deciduous timber vary in dependence of their main use: material and energetic purpose. In Germany for example, material purposes mainly require coniferous timber (78 – 89 %), whereas energetic purposes are dominated by deciduous timber (43 – 57 %) (Jochem et al. 2015). This means that only a small amount of the harvested deciduous timber is used for high-quality material purposes in the first processing stage. These differences in timber usage are not primarily a result of supply but of processing possibilities (Ammann et al. 2016; Konnerth et al. 2016; Aicher et al. 2018), consumers preferences (Gartner 2005) and different wood properties (Spellmann 2005). Coniferous and deciduous timber differs in anatomical structure and complexity (e.g., Matyssek et al. 2010). The woody tissue of deciduous trees, which is younger in terms of phylogenetic development, shows specialized cell types for different functions, e.g., wood vessels for water transportation or fibers for mechanical support (Matyssek et al. 2010). This results in different physical, mechanical, and chemical properties when compared to coniferous timber. Therefore, a substitution of coniferous timber by deciduous timber is not readily possible for all products (Schier et al. 2018) and it becomes important to investigate influences on deciduous timber quality as it is neither ecologically nor economically sustainable to use such a high proportion of 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 competition (Höwler et al. 2017; Burkardt et al. 2019). With an increasing species diversity in mixed forest stands, neighborhood diversity might also increase and it becomes important to understand how timber quality of a stem is influenced by different neighboring species. On the one hand, mixed forest stands are of higher structural heterogeneity (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 decreased 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 natural pruning of the lower and most valuable stem section on crop trees and consequently increase timber quality (Bauhus et al. 2017b). However, timber quality is also further influenced by the silvicultural treatments applied. Hence, the effect of mixed-species neighborhoods on the timber quality of a target tree can be expected to depend on species interactions, competition abilities, and species compositions (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). However, silvicultural management can control the amount, condition and size of branches. For example, small branches and natural pruning can be promoted by keeping a stand dense through high competition in an early management phase (e.g., Hein 2008). As soon as the preferred length of the branch-free stem is achieved, diameter increase can be fostered by crown release (e.g., Hein 2008). The branches are small, occlude fast and as a result, the knotty core inside the log is small and stops at the first living branch (Hein 2008; Kint et al. 2010).

Therefore, forest management should keep the occlusion process of branches short (Hein 2008). In order to evaluate and compare the internal timber quality of one of the most important deciduous tree species in Central Europe (Knoke 2003) - European beech (*Fagus sylvatica* L.) - tree logs from mixed and pure forest stands were investigated, pursuing the following questions:

1. How is the timber quality attribute *knot surface* distributed along the horizontal and vertical stem axis?
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 and decreases along the horizontal stem axis as a results of the applied silvicultural treatment (keeping stands at high densities until self-pruning has reached around 8 m stem length, followed by cuttings that remove competitors from target tree while increasing their diameter growth). 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.

4.2. Methods

The horizontal and vertical distribution of the timber quality attribute *knot surface* 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 4.1). 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 - 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.

Table 4.1 Description of the study sites from the forest districts Ebergötzen (formerly Husum), Reinhausen, and Sattenhausen based on Höwler et al. (2017). For further information on the forest stands the reader is referred to Höwler et al. (2017) and Höwler et al. (2019).

	Ebergötzen (formerly Husum)		**Reinhausen**							**Sattenhausen**			
Location (degree, minutes, seconds)	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	301 – 350	351 – 400	251 – 300
Department no.	1065	1068	10	14	16	18a	18e	34	37	1024	1033	1039	1043
Area [ha]	6.2	4.0	14.6	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	BeSp	Be	BeDgl	Be	BeSp	BeSp	BeDgl	BeDgl	BeAsMa	BeAsMa	BeAsMa
Harvested sample trees	5	5	10	20	5	10	5	5	5	5	5	5	5
Main tree species	Be	Be	Be	Be	Dgl	Be	Be	Be	Dgl	Be	Be	Be	Be
Age [a]	88	88	79	72	53	93	90	85	62	90	111	93	73
Standing volume [m³/ha]	229	186	168	215	316	375	172	316	188	337	361	300	159
Top height [m]	30.2	30.2	30.8	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	38	33	28	31	39	34	39	36	26
Heavy crown thinning (last 6 years) [m³/ha]	0.0	15.9	40.2	0.0	3.7	0.0	62.0	12.2	12.1	93.2	54.0	10.3	7.3

***Be**, pure beech; **BeAsMa**, beech mixed with ash and maple; **BeDgl**, beech mixed with Douglas-fir; **BeSp**, beech mixed with spruce

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 4.2). For this study, we analyzed the boards of the first two log sections (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).

Table 4.2 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. Given 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.

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

Each board was photographed lengthwise using a single-lens reflex camera, 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. 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 (Figure 4.1). 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).

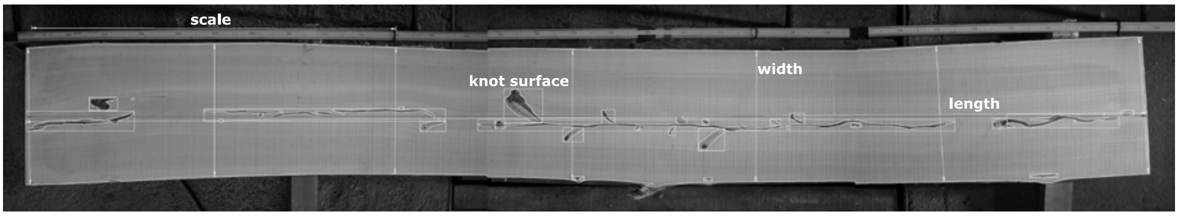

Figure 4.1 Measurement of one board using the software Datinf® Measure including the total length, the widths assessed every 50 cm, *knot surfaces,* and the total board surface. The scale on the measuring tape equaled 100 cm and enabled a transformation from pixel into metric units (created using IrfanView version 4.42 and Inkscape version 0.92).

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 Figure 4.2).

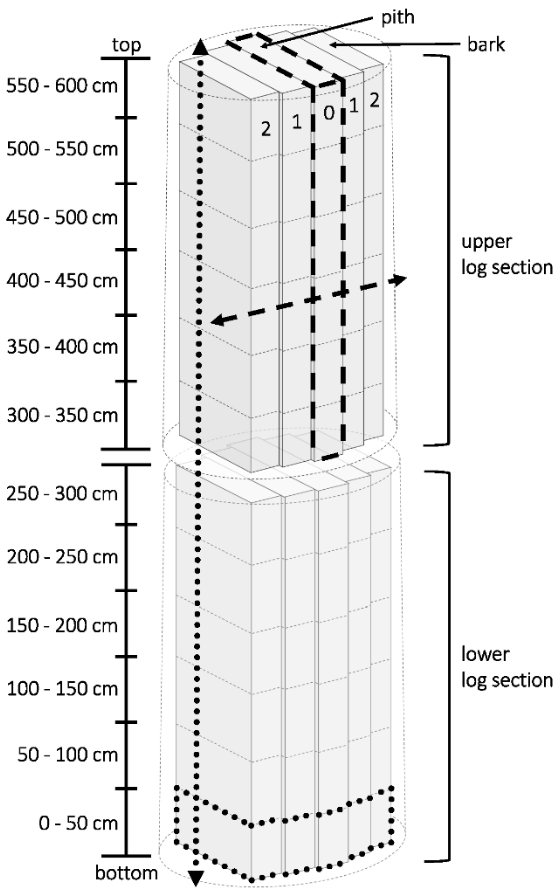

Figure 4.2 Exemplary virtual composition of the boards of one European beech sample tree with two log sections of 3 m length each (lower log section: 0 - 300 cm, upper log section: 300 - 600 cm) and an unequal number of boards (n = 5). Shown are the central board (group 0, equals the median board) and 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).

4.2.1. 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 sections (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 for the 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 of a group of boards was then multiplied by the board thickness (min. 21 mm, max. 50 mm) to receive the distance of the boards to the determined center of the logs. Offcuts were excluded from this study so that the maximum radius of the logs was 200 mm.

4.2.2. Vertical distribution of knot surface

The lower (3 - 5 m height) and upper (6 - 10 m height) log sections of each sample tree were virtually merged to investigate the vertical distribution of the timber quality attribute *knot surface* from bottom to top (Figure 4.2). These merged log sections were then virtually 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 ending 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 equation 4.1:

$$\textit{knot surface}_{\text{0-50 cm}}\ [\%] = \left(\frac{\sum_{i=1}^{n} \text{knot surfaces}_{i\ \text{0-50 cm}}\ [\text{cm}^2]}{\sum_{i=1}^{n} \text{board surfaces}_{i\ \text{0-50 cm}}\ [\text{cm}^2]}\right) * 100 \tag{4.1}$$

Since the log sections varied in length (due to the commercial sawing procedure), we used relative heights.

4.2.3. Statistical analysis

All statistical analyses were performed using the free and open-source-software R (version 3.4.4, R Core Team 2018) with a significance level of $p < 0.05$.

4.2.3.1. Horizontal distribution of knot surface

The horizontal distribution of *knot surface* was analyzed for different *forest mixture types* using several linear and non-linear regression models (Table 4.3) following Allan et al. (2014). The approach of Allan et al. (2014) was chosen as it allowed to model a diversity of shapes for the relationship between *knot surface* and *distance to the central board* for different *forest mixture types* and to subsequently calculate Akaike's information criterion for small sample sizes (AICc) to select the best-adapted model. The *forest mixture type* was modelled as a covariate in dependence on (i) intercept and/ or slope (negative exponential), and on (ii) intercept, horizontal asymptote, rate constant, or on all three parameters (asymptotic exponential). The non-linear regression models were fitted using the 'gnls function' of the 'nlme package' (Pinheiro et al. 2020).

Table 4.3 Description of the applied regression models following Allan et al. (2014) with y = *knot surface* [%] and x = *distance to central board* [mm] for all models. Negative exponential: a = intercept, b = slope. Asymptotic exponential: a = horizontal asymptote, b = a – R0 (with R0 = intercept), c = rate constant (Crawley 2007).

Model description	Formula	Model variations
linear quadratic cubic	$y = a + bx$ $y = a + bx + cx^2$ $y = a + bx + cx^2 + dx^3$	• *distance to central board + forest mixture type* • *distance to central board * forest mixture type*
negative exponential	$y = ae^{-bx}$	• intercept as function of *forest mixture type* • intercept, slope as function of *forest mixture type*
asymptotic exponential	$y = a - be^{-cx}$	• intercept as function of *forest mixture type* • asymptote as function of *forest mixture type* • rate constant as function of *forest mixture type* • asymptote, rate constant as function of *forest mixture type* • asymptote, intercept as function of *forest mixture type* • rate constant, intercept as function of *forest mixture type* • intercept, asymptote, rate constant as function of *forest mixture type*
power law	$y = a + bx^c$	• intercept as function of *forest mixture type* • all parameter as function of *forest mixture type*

In order to investigate the influence of different tree species mixtures on *knot surface*, the four *forest mixture types* were subsequently grouped to all possible combinations (e.g., pure beech stand and mixed beech stand with spruce against mixed beech stand with ash and maple and mixed beech stand with Douglas-fir) according to AICc theory. This resulted in 14 possible combinations. The full model was then tested against the reduced models by means of deltAICc comparison. We selected the simplest model with a deltAICc < 2 as the best-adapted model.

4.2.3.2. 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 attributes only reached positive values.

4.3. Results

4.3.1. Horizontal distribution of knot surface

The model selection with a subsequent deltAICc comparison revealed that the best model to describe the relationship between *knot surface* and *distance to central board* was a negative exponential model with the intercept as a function of *forest mixture type* (supporting information, Table 4.7 and Table 4.8). This was true for both the lower (R^2_{pseudo} = 0.47) and upper (R^2_{pseudo} = 0.32) log sections (Table 4.4). For the lower log sections, generalized nonlinear least squares analyses suggested differences between pure beech stands (p = 0.003, Table 4.4) and mixed stands with spruce (p < 0.001). For the upper log sections, differences between beech trees from mixed stands with spruce (p < 0.001) and beech trees from all other mixtures (ash and maple (p = 0.014), Douglas-fir (p = 0.004), pure beech (p = 0.008); Table 4.4) were assumed.

Table 4.4 Results of the generalized nonlinear least squares fit (negative exponential, intercept as function of forest mixture type) to describe the relationship between the response variable *knot surface* [%] dependent on *distance to the central board* [mm] as well as on *forest mixture type* as explanatory variables along the horizontal stem axis for the lower and upper log sections. Given are the model parameters slope and intercept for the four forest mixture types, parameter values (value) with their standard errors (SE), t-statistics (*t* value), model significance (*p* value), and pseudo *R* squared (R^2_{pseudo}).

Log section	Model parameter	Value	SE	*t* value	*p* value	R^2_{pseudo}
Upper	Slope	0.009	0.003	3.623	< 0.001	0.32
	Beech + spruce (intercept)	1.197	0.172	6.952	< 0.001	
	Beech + ash, maple	-0.539	0.214	-2.525	0.014	
	Beech + Douglas-fir	-0.586	0.196	-2.988	0.004	
	Beech	-0.526	0.190	-2.774	0.008	
Lower	Slope	0.013	0.002	6.795	< 0.001	0.47
	Beech + spruce (intercept)	0.774	0.088	8.801	< 0.001	
	Beech + ash, maple	-0.189	0.122	-1.547	0.126	
	Beech + Douglas-fir	-0.116	0.099	1.168	0.246	
	Beech	-0.331	0.109	-3.053	0.003	

A subsequent comparison of all possible combinations of *forest mixture type* groups following deltAIC theory showed that for the lower log sections seven out of 14 models were within deltAICc < 2 and had a rather low support of AICc weight at most 18 % (Table 4.5). Here, the simplest and best model was the combination of the *forest mixture type* groups beech mixed with spruce and beech mixed with Douglas-fir (mixture group 13, Table 4.5) against beech mixed with ash and maple combined with pure beech (mixture group 24, Table 4.5). Regarding the upper log sections, four reduced models performed better compared to the full model, and in these models, the mixture of beech with spruce (mixture group 1, Table 4.5) was always separated. Here, the best model was the combination of *forest mixture type* groups beech mixed with ash and maple, mixed with Douglas-fir and pure beech (mixture group 234, Table 4.5) against beech mixed with spruce (mixture group 1, Table 4.5) with a deltAICc < 2 and a high support of AICc weight at 47 %.

Table 4.5 Comparison of the generalized nonlinear least squares fits (negative exponential, intercept as function of *forest mixture type*) of different *forest mixture type* group combinations to analyze the effect of tree species mixing on *knot surface* [%] along the horizontal stem axis for the lower and upper log sections. The four best-adapted reduced models are presented in comparison to the full model (cf. Table 4.4; supporting information Table 4.7 and Table 4.8). Given are the *forest mixture type* groups (**1** = beech and spruce; **2** = beech and ash, maple; **3** = beech an Douglas-fir; **4** = pure beech), number of factors (*n* of factors), log-likelihood (LL), small sample-size adjusted Akaike-Information-Criterion (AICc), and model support (weight).

Log section	Forest mixture type groups			*n* of factors	Model rank	LL	AICc	deltAICc	weight
Upper	234	1		2	1	-18.401	45.504	0.000	0.47
	24	1	3	3	2	-18.351	47.773	2.269	0.15
	23	1	4	3	3	-18.373	47.817	2.313	0.15
	34	1	2	3	4	-18.398	47.867	2.363	0.15
	Full model			4	5	-18.349	50.225	4.721	0.04
Lower	23	1	4	3	1	30.146	-49.523	0.000	0.18
	13	24		2	2	28.982	-49.457	0.066	0.17
	123	4		2	3	28.861	-49.215	0.308	0.15
	24	1	3	3	4	29.694	-48.619	0.904	0.11
	Full model			4	7	30.333	-47.575	1.948	0.07

The generalized non-linear least square fit for the selected best-adapted model revealed a significant relationship between the quality attribute *knot surface* and *distance to the central board* for the lower and upper log sections (Figure 4.3a and Figure 4.3b, Table 4.9 supporting information): with increasing *distance to the central board* the *knot surface* decreased by 0.013 % for the lower and by 0.009 % for the upper log sections. As expected, the *knot surface* was larger for boards close to the pith and decreased towards the bark. Furthermore, larger *knot surfaces* were observed for the upper log sections, including a greater visual dispersion compared to the lower log sections (Figure 4.3a and Figure 4.3b).

For the lower log sections, European beech trees from pure beech stands had smaller internal *knot surfaces* (0.44 %) compared to European beech trees from mixed forest stands (0.69 %). Similarly, beech trees from pure stands showed consistently smaller *knot surfaces* along the entire horizontal stem axis compared to beech trees from mixed stands (Figure 4.3b).

For the upper log sections, largest internal *knot surfaces* (1.19 %) were observed for European beech trees from mixed forest stands with Norway spruce. Additionally, these sample trees showed consistently larger *knot surfaces* along the entire horizontal stem axis (Figure 4.3a).

Overall, however, it should be noted that *knot surface* per board group was at most 2 % along the horizontal stem axis of the investigated European beech trees.

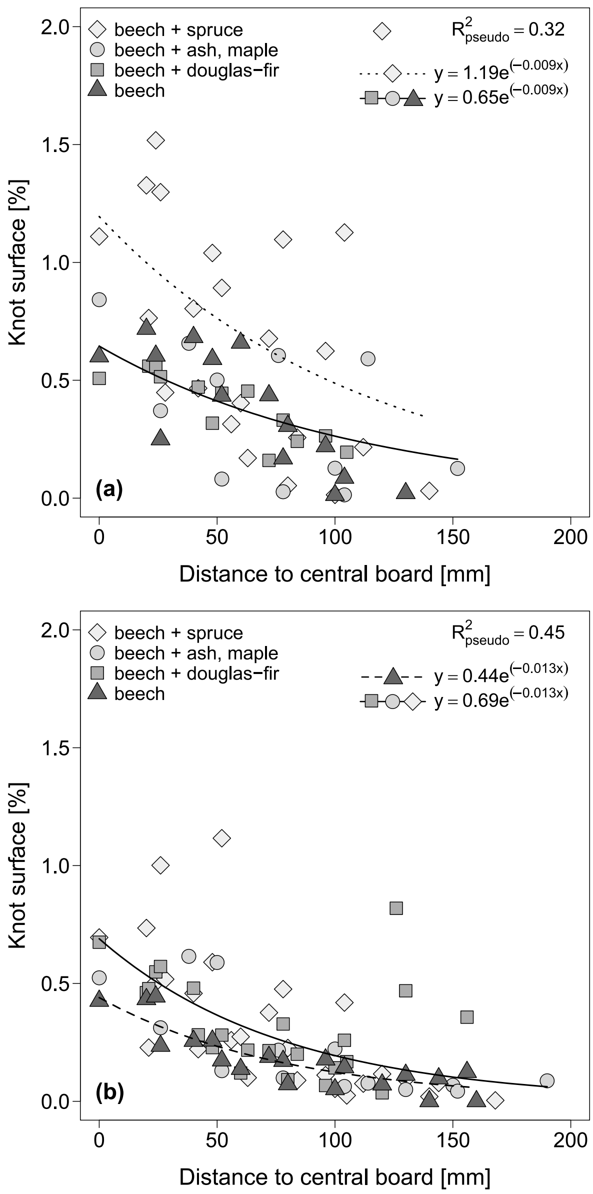

Figure 4.3 Relationship between *distance to the central board* [mm] and *knot surface* [%] for **(a)** the upper log sections (6 - 10 m height) and **(b)** the lower log sections (3 - 5 m height) of European beech trees from mixed forest stands with Norway spruce, with ash and maple, with Douglas-fir, and from pure beech stands. The lines refer to the applied negative exponential non-linear least square models ($y = ae^{-bx}$). Only significant relationships at $p < 0.05$ are presented.

4.3.2. Vertical distribution of knot surface

GLMs were applied to examine the relationship between the quality attributes *knot surface* and *relative log height* of European beech trees from four *forest mixture types*. The GLM analysis revealed a significant positive relationship between *knot surface* and *relative log height* ($p < 0.001$, $R^2_{pseudo} = 0.043$) for European beech trees from pure beech stands, from mixed stands with Douglas-fir, or from mixed stands with Norway spruce (Table 4.6): With increasing *relative log height,* the quality attribute *knot surface* increased (0.004 ± 0.001 % *knot surface*), however this relationship was very weak. At 0 % *relative log height*, beech trees from mixture with Norway spruce showed 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 %.

Table 4.6 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*. 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}).

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 (Intercept)	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	

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* (Figure 4.4). When mixed with ash and maple the relationship was not significant. Expressed in absolute values, 100 % *relative log height* 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).

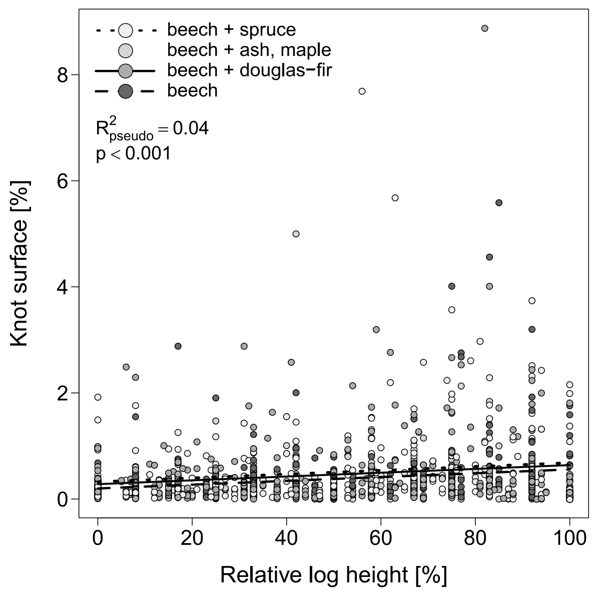

Figure 4.4 Relationship between *relative log height* [%] and *knot surface* [%] of European beech trees from mixed forest stands with Norway spruce, with ash and maple, with Douglas-fir, and from pure beech stands. The lines refer to the applied generalized linear models with gamma family distribution. Only significant relationships at $p < 0.05$ are presented.

4.4. Discussion

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

The first 10 m of deciduous logs are of high economic interest, because they make up to 80 % of the timber value (Bachmann 1970). Timber quality of a tree is e.g., related to the branch characteristics and 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 (Grace et al. 1998). Therefore, influencing branchiness by varying thinning intensities, stand densities, and thus competition is a major silvicultural tool to control the number of branches and branch diameters in the most valuable part of the logs (Mäkinen and Hein 2006). Maintaining a high stand density in early developmental phases (length varies in dependence of tree species) reduces knottiness inside the log towards a small knotty core, because it increases self-pruning and decreases branch diameter development which in turn fosters rapid occlusion processes (Kint et al. 2010; Höwler et al. 2017; Benneter et al. 2018). Once self-pruning has taken place, reduction in stand density may be applied fostering crown expansion and, subsequently, diameter growth of the remaining trees (e.g., Hein 2008; Pretzsch 2019). In the end, larger and thicker branches are found in the upper parts of the stem because low competition does not restrict branches development there, while the lower part of the stem becomes a clear bole. In fact, in our study the *knot surfaces* significantly increased with increasing *relative log height*, but this relationship was rather weak. Since the crown of a tree moves to a higher stem section and the branch-free zone inside of a log becomes greater by diameter growth, larger parts of wood unaffected by branches are found along the horizontal stem axis in the lower stem section. This holds true for the investigated European beech trees from this study 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 treatment up to the day of harvest has effectively reduced knottiness in the lower and most important stem sections as well as in the outer boards of the logs and 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 (keeping stands at high densities until self-pruning has reached around 8 m stem length, followed by cuttings that remove competitors from target tree while increasing their diameter growth). Nevertheless, hypothesis (i) could not be fully accepted due to the rather weak relationship for the distribution of *knot surface* along the vertical stem axis.

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

The effect of neighborhood species identity on timber quality is of high economic interest. We hypothesized that neighborhood species identity affects timber quality of European beech trees. More specifically, we expected higher timber quality in 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 natural pruning and reduced knottiness. Since we observed higher timber quality in terms of smaller *knot surface* in pure beech stands, our results support hypothesis (ii) that the timber quality attribute *knot surface* is smaller in pure compared to mixed beech stands due to higher competition intensity of beech itself. 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 described as cone-shaped, as comparably narrow and triangular, whereas beech crowns are described as 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). Therefore, in mixture with spruce a more heterogeneous horizontal and vertical structure allows light to reach lower canopy layers in mixed forest stands leading to delayed crown-uplifting (Pretzsch and Rais 2016), which consequently may lead to the development of more branches and a delay in self-pruning compared to pure beech stands (cf. Bayer et al. 2013). Also, 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). Hypothesizing that beech exposes highest intraspecific competition (Dieler 2011; Metz et al. 2013), sample trees might 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, also the central boards were knottier. This might be because even at young ages spruce enforces less competition compared to beech, but also that the forest stands have grown differently dense due to different ecological requirements. Consistently, smallest values of *knot surface* along the vertical stem axis were observed in pure beech stands and largest in mixture with Norway spruce. This also supports the finding that highest competitive pressure in beech stands is caused by beech neighboring itself (Dieler 2011; Metz et al. 2013).

Although the values for *knot surface* were small, we observed significant differences between mixed and pure forest stands and could show that the applied method was sensitive to detect these differences despite of small values for *knot surface*. The results have demonstrated that *knot surface* on the horizontal and vertical stem axis appears to be differently affected by different neighborhoods, which implicitly means that it can be controlled through silvicultural measures. In our study, the investigated forest stands are commercially managed and have undergo 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 tree was classified in grade A (best quality) or grade D (bad quality). Earlier studies revealed 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 confirm 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 spruce and Douglas-fir. 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 and highlights the importance of continuing to study the effect of neighborhood species identity on timber quality in mixed forest stands.

4.5. Conclusion

In this study, we analyzed the effects of neighborhood species identity on timber quality attributes and their distribution along the horizontal and vertical stem axis of European beech trees from mixed compared to pure forest stands. Here, we observed a tendency towards higher timber quality in pure beech stands at high intraspecific competition intensity, but the values for *knot surface* were small. Despite of small values of *knot surface*, the observed differences between pure and mixed beech stands were statistically significant. In fact, even though comparatively good timber quality grades and a consistently rather small *knot surface* were found in mixed stands we were able to detect significant differences between the stand types. Thus, although mixed forest stands are advantageous in several respects, a tendency towards lowered timber quality of European beech trees can be expected in mixed compared to pure beech stands. However, in this study the differences were small and did not change the timber value. Since the actual outcome of timber quality seems to depend on the admixed tree species, stand management regime and hence forest structure, which was not investigated here, no generalizations are possible. Nevertheless, adequate silvicultural treatments in terms of regulating 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. Mixed forest stands still provide many beneficial characteristics (Knoke et al. 2008) and can better fulfill multiple ecosystem services (van der Plas et al. 2016). As the percentage of European beech trees on total stand basal area and thus intraspecific competitive effects were high even in the investigated mixed stands, our study points towards block-wise mixtures instead of single tree mixtures. The former might offer an ideal compromise to benefit from intraspecific competitive effects for timber quality (natural pruning is stronger and branchiness reduced), but also establish mixed stands on a landscape level (Tiebel et al. 2016). For other forest properties making more use of 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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Conflict of interest statement

None declared.

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Supporting information

Table 4.7 Results of the deltAICc comparison of all fitted regression models following Allan et al. (2014) for the lower log sections. Given are the rank according to deltAICc comparison, model name and equation, log-likelihood (LL), Akaike-Information-Criterion corrected for small sample sizes (AICc), and model support (*w*).

Rank	Model name	Model equation	LL	AICc	deltAICc	*w*
1	**Negative exponential, intercept as function of *forest mixture type***	**a * exp(-b * *distance*)**	**30.333**	**-47.575**	**0.000**	**0.37**
2	Quadratic, *distance* * *forest mixture type*	poly(*distance*, 2) * *forest mixture type*	38.292	-45.384	2.191	0.12
3	Asymptotic exponential, intercept as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	30.368	-45.262	2.313	0.12
4	Negative exponential, *distance*	a * exp(-b * *distance*)	25.228	-44.157	3.418	0.07
5	Asymptotic exponential, asymptote and rate constant as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	33.512	-44.010	3.565	0.06
6	Quadratic, *distance* + *forest mixture type*	poly(*distance*, 2) + *forest mixture type*	29.708	-43.943	3.632	0.06
7	Quadratic, *distance*	poly(*distance*, 2)	25.441	-42.376	5.199	0.03
8	Negative exponential, all parameters as function of *forest mixture type*	a * exp(-b * *distance*)	31.277	-42.122	5.453	0.02
9	Asymptotic exponential, asymptote and intercept as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	32.516	-42.017	5.557	0.02
10	Asymptotic exponential, *distance*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	25.233	-41.959	5.616	0.02
11	Asymptotic exponential, rate constant as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	28.586	-41.698	5.877	0.02
12	Cubic, *distance* + *forest mixture type*	poly(*distance*, 3) + *forest mixture type*	29.728	-41.536	6.038	0.02
13	Asymptotic exponential, asymptote as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	28.060	-40.646	6.928	0.01
14	Cubic, *distance*	poly(*distance*, 3)	25.453	-40.136	7.439	0.01
15	Power law, intercept as function of *forest mixture type*	a + b * (*distance*^c)	27.770	-40.067	7.508	0.01
16	Asymptotic exponential, rate constant and intercept as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	31.456	-39.898	7.677	0.01
17	Power Law, *distance*	a + b * (*distance*^c)	24.008	-39.510	8.065	0.01
18	Linear, *distance* * *forest mixture type*	*distance* * *forest mixture type*	29.827	-39.221	8.354	0.01
19	Asymptotic exponential, all parameters as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	35.142	-39.084	8.491	0.01
20	Linear, *distance*	*distance*	22.425	-38.549	9.025	0.00
21	Linear, *distance* + *forest mixture type*	*distance* + *forest mixture type*	25.669	-38.248	9.327	0.00
22	Cubic, *distance* * *forest mixture type*	poly(*distance*, 3) * *forest mixture type*	39.071	-34.870	12.705	0.00
23	Power law, all parameters as function of *forest mixture type*	a + b * (*distance* ^c)	32.697	-34.194	13.381	0.00
24	*mixture type*	*mixture type*	6.934	-3.099	44.476	0.00

Table 4.8 Results of the deltAICc comparison of all fitted regression models following Allan et al. (2014) for the upper log sections. Given are the rank according to deltAICc comparison, model name and equation, log-likelihood (LL), Akaike-Information-Criterion corrected for small sample sizes (AICc), and model support (*w*).

Rank	Model name	Model equation	LL	AICc	deltAICc	*w*
1	**Negative exponential, intercept as function of *forest mixture type***	**a * exp(-b * *distance*)**	**-18.349**	**50.2253**	**0.0000**	**0.30**
2	Linear, *distance* + *forest mixture type*	*distance* + *forest mixture type*	-18.551	50.6285	0.4032	0.25
3	Quadratic, *distance* + *forest mixture type*	poly(*distance*, 2) + *forest mixture type*	-17.823	51.7193	1.4940	0.14
4	Power law, intercept as function of *forest mixture type*	a + b * (*distance*^c)	-18.235	52.5443	2.3190	0.09
5	Asymptotic exponential, intercept as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	-18.283	52.6397	2.4144	0.09
6	Cubic, *distance* + *forest mixture type*	poly(*distance*, 3) + *forest mixture type*	-17.809	54.3341	4.1088	0.04
7	Asymptotic exponential, rate constant as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	-19.720	55.5145	5.2892	0.02
8	Asymptotic exponential, asymptote as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	-19.789	55.6524	5.4271	0.02
9	Negative exponential, all parameters as function of *forest mixture type*	a * exp(-b * *distance*)	-18.025	57.5107	7.2854	0.01
10	Negative exponential, *distance*	a * exp(-b * *distance*)	-25.571	57.5562	7.3308	0.01
11	Linear, *distance* * *forest mixture type*	*distance* * *forest mixture type*	-18.377	58.2146	7.9893	0.01
12	Linear, *distance*	*distance*	-26.003	58.4195	8.1941	0.01
13	Asymptotic exponential, asymptote and intercept as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	-17.623	59.5593	9.3340	0.00
14	Quadratic, *distance*	poly(*distance*, 2)	-25.462	59.6246	9.3993	0.00
15	Asymptotic exponential, *distance*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	-25.522	59.7462	9.5209	0.00
16	Power Law, *distance*	a + b * (*distance* ^c)	-25.823	60.3468	10.1215	0.00
17	Asymptotic exponential, rate constant and intercept as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	-18.020	60.3538	10.1285	0.00
18	*forest mixture type*	*forest mixture type*	-24.953	60.9772	10.7519	0.00
19	Cubic, *distance*	poly(*distance*, 3)	-25.460	61.9918	11.7665	0.00
20	Asymptotic exponential, asymptote and rate constant as function of *forest mixture type*	Asym + (R0 - Asym) * exp(-exp(lrc) * *distance*)	-19.287	62.8878	12.6625	0.00
21	Quadratic, *distance* * *forest mixture type*	poly(*distance*, 2) * *forest mixture type*	-16.260	66.1046	15.8793	0.00
22	Power law, all parameters as function of *forest mixture type*	a + b * (*distance*^c)	-17.216	68.0148	17.7895	0.00
23	Cubic, *distance* * *forest mixture type*	poly(*distance*, 3) * *forest mixture type*	-15.505	78.9192	28.6939	0.00

Table 4.9 Results of the best-adapted generalized nonlinear least square 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*. Given are the model parameters slope and intercept for the *forest mixture type* groups (**1** = beech and spruce; **2** = beech and ash, maple; **3** = beech and Douglas-fir; **4** = pure beech), model parameter values (value) with their standard errors (SE), t-statistics (*t* value), and model significance (*p* value).

Log section	Model parameter	Value	SE	*t* value	*p* value
Upper	intercept (**1**)	0.645	0.106	6.058	0.00
	intercept (**234**)	0.550	0.154	3.582	< 0.001
	slope	0.009	0.002	3.662	< 0.001
Lower	intercept (**4**)	0.440	0.087	5.068	< 0.001
	intercept (**123**)	0.250	0.094	2.653	0.010
	slope	0.013	0.002	6.745	< 0.001

Chapter 5

Synthesis

5. Synthesis

The commercial value of harvested logs is mainly driven by timber quality (Bauhus et al. 2017b) and timber quality of a single tree is substantially influenced by the intensity of competition enforced by neighbouring trees (Zingg and Ramp 2003; Höwler et al. 2017). High competitive pressure through high stand density leads to stronger self-pruning and can therefore reduce the number of branches, the branch diameter, and thus knottiness (Mäkinen and Hein 2006). Also, the initiation of discoloration inside a log can be promoted by larger branches due to longer occlusion times and an increased probability for entering oxygen (Wernsdörfer et al. 2005). Since competition plays an essential role in influencing tree growth and thus timber quality it must be controlled by silvicultural treatments, e.g., through regulating stand density. However, considerable competitive differences can be observed in pure and mixed forest stands due to differing growing conditions: in pure forest stands, trees occupy the same ecological niche with high intraspecific competitive pressure, whereas in mixed stands complementary effects can occur, leading to relaxed interspecific competition (Ammer 2017; Pretzsch et al. 2017). Given the ongoing changing and uncertain future climate conditions, forest conversion from pure to mixed forest stands and thus changed timber availability, the main research questions were introduced as follows:

(1) How does increasing competition affect the timber quality characteristics of European beech?

(2) What influence does neighbourhood species identity have on the timber quality characteristics of European beech?

(3) Are the quality features on the bark surface of the stem in accordance with the internal timber quality?

(4) How are timber quality features distributed along the horizontal and vertical stem axis?

(5) Do the numerous advantages of mixed forest stands come at the expense of quality?

In this chapter, the main findings of the presented three studies are summarized and discussed.

5.1. Effect of intra- and interspecific competition on branchiness

Branch scars on the bark surface of smoothly barked tree species can be used as an indicator for internal timber quality. In this way, Schulz (1961) showed that the ratio of branch scar height to branch scar width is related to the depth of the corresponding knot inside a log for European beech trees. Dead branches or branch stumps become occluded and subsequently clear wood is formed around the knotty core (Stängle et al. 2014). Thus branch scars can be used to estimate the ratio between the knotty core and the clear wood content inside a log, which is an important quality grading criterion (Stängle et al. 2014). Therefore, the occurrence of irregularities on the bark surface (e.g., branch scars, bumps), which were here summarized as bark anomalies, was investigated on all sample European beech trees. Moreover, the effect of intra- and interspecific competition intensity on bark anomalies as well as the relationship between external bark irregularities and internal knottiness was tested.

Externally, the investigated European beech trees showed a significantly lower number of bark anomalies in all three stem sections (0 – 5 m, 5 – 10 m, 10 – 15 m) when competition intensity was high (Chapter 2). In addition, the number of bark anomalies decreased from the first stem section (0 – 5 m) to the third stem section (10 – 15 m). Thus, the length of the branch-free bole increased with increasing competition intensity as a result of shading by neighbouring trees. This is in agreement with Burkardt et al. (2019), who conducted the herein developed methodology to assess external stem quality characteristics using TLS on red oak (*Quercus rubra* L.) and observed a decreasing number of bark anomalies with increasing competition intensity. Most likely, high competition intensity, because of higher stem densities or larger neighbours, reduced the light availability and thus promoted self-pruning. This should in turn result in fewer branches, in thinner branches dying earlier, in fewer branch scars on the bark surface, in fewer knots on the sawn board surface and hence in an increased timber quality (Richter 2019). This specific relation could be confirmed here, although neither the relation between knot surface per tree and competition intensity (Chapter 3, Figure 3.4b, p. 75) nor between the number of bark anomalies and the knot surface per tree was significant (Chapter 3, Table 3.3, p. 78). Yet, at high competition intensity (> 1.5) – which simultaneously implies a lower number of bark anomalies – no larger knot surfaces per tree (> 0.1 %) on the sawn board surface were found (Figure 3.4b, p. 75). This finding was further supported by investigating the effects of intra- and interspecific competition on knottiness: First, no significant differences in knot surface per tree were found between the four mixture types. However, by narrowing the observation scale from the tree level (Chapter 3) to the board level (Chapter 4), significant differences between the four mixture types became apparent. The knot surfaces were significantly larger on sawn beech boards from mixed forest stands of beech with Norway spruce or with Douglas-fir while smallest knot surfaces were observed on beech boards from pure beech stands.

The question that arises here is whether the main factor determining knottiness as a measure for timber quality is the degree of competition per se or rather the identity of the neighbouring tree species and thus the way how tree species compete (e.g., fast growth behaviour, lateral shade, crown transparency). On the one hand, highest degrees of competition were measured in the investigated pure beech stands. This is in line with, for example, Dieler (2011) or Metz et al. (2013; 2016), who described beech itself as its strongest competitor. High intraspecific competitive pressure in pure beech stands probably led to higher natural pruning, lower branchiness, and thus smaller knot surfaces. Examining the distribution of knots along the horizontal and vertical stem axis led to similar findings: inner boards (near pith) showed larger and outer boards (near bark) smaller knot surfaces. Additionally, knot surfaces significantly increased with increasing relative log height. This may be the result of a silvicultural management system in which stand densities in an early developmental phase were maintained high to promote self-pruning, to keep branch diameters, the occlusion times, and the knotty core small, and to hence increase the length of the clear bole (Hein 2008; Kint et al. 2010). As soon as the preferred length of the clear bole was achieved, greater crown thinning operations were performed to then promote crown expansion and diameter growth (e.g., Hein 2008; Pretzsch 2019). Furthermore, with increasing height growth, the crown of a tree shifts upwards and the clear wood content inside of a log increases in the lower stem sections. This implies that trees from denser stands have their strongest and thickest branches in the upper parts of the stem while the knotty core is small and the length of the lower clear bole is increased. The degree of competition may therefore have effectively reduced knottiness.

On the other hand, the tree species identity of the neighbouring trees may also have influenced knottiness through the way each species competes (growth behaviour, shading, crown transparency). For example, spruce is less competitive compared to beech (Dieler 2011). Furthermore, beech and spruce have different ecological requirements for e.g., light or soil (Bartsch et al. 2020). While for example beech has a high shade tolerance, spruce is considered a semi-shade tree species (Bartsch et al. 2020). Also, the crown extension for deciduous trees tends to be horizontal while for conifers it is rather vertical or pyramidal (Pretzsch 2019). Therefore, processes in mixed forest stands differ from those in pure stands, which can be explained e.g., by changed growing conditions, competition for light or nutrients, but also by density effects (Biber et al. 2013). Compared to pure beech stands, mixed stands of beech and spruce grow differently dense. Hence, boards from mixed forest stands with beech and spruce not only had a larger total knot surface, but also stronger knotted central boards, due to lower competition intensity of spruce - even at young ages. When competition intensity is high (intra- or interspecific), natural pruning is fostered, less branches occur, the bark surface is more regular and the clear wood content around the knotty core increases (Stängle et al. 2014). This might also explain the non-significant relationship between the number of bark anomalies on the bark surface and the internal knot surface.

However, also a contradictory result was observed between a consistently decreasing number of bark anomalies with increasing log height (0 – 5 m, 5 – 10 m, 10 – 15 m, Chapter 2) and an increasing knot surface with increasing relative log height (100 % log height between 6 and 10 m, Chapter 4). This implies that less branch scars were observed externally with increasing log height but internally the knot surfaces increased with increasing log height. Possibly, this could be explained by the horizontal distribution of knots, since the knot surfaces decreased with increasing distance from the pith. This indicates that branches have already been occluded and are externally non-detectable for the TLS-approach. Furthermore, lower values of bark anomalies were observed in the third log sections (10 – 15 m) and the internal knot surface was only investigated until a maximum height of 10 m. In the upper log sections (10 – 15 m) the density of the point cloud was additionally lower due to occlusion by branches and leaves. This might have also influenced the detection of bark anomalies in the upper log sections of the investigated trees.

In summary, the results have shown that knottiness is influenced by competition intensity. Also neighbourhood species identity and thus intra- and interspecific competition seemed to influence knottiness differently. Depending on the admixed tree species, neighbourhood species identity may naturally be linked to competition intensity as the growth behaviour and ecological requirements of species determine their competitive ability. Therefore, it can be assumed that competition intensity itself is probably the main contributing factor for lower knottiness and thus increased timber quality. Consequently, silvicultural strategies to manage tree species mixing, stand density, and in turn competition intensity can control the degree of branching and knottiness. The results further showed that the applied silvicultural treatment effectively reduced knottiness in the lowest and most important log sections of the investigated European beech trees. Admittedly, the area of the measured knots was small. Nevertheless, the results showed that the applied method was sensitive to detect these differences despite of small values and indicate that timber quality (as a result of the past) is related to even the current competitive situation. A low degree of competitive pressure will not necessarily lead to pronounced knottiness. However, high competitive pressure will certainly reduce branchiness.

5.2. Effect of intra- and interspecific competition on discoloration

The discoloration surface is ranked as one of the most important factors influencing the consumer preferences for European beech wood (Knoke et al. 2006). Discoloration can cause a substantial value loss of logs, as homogenous light-coloured beech wood is preferred in industrial processing (Wernsdörfer et al. 2005; Wernsdörfer et al. 2006). The discoloration thus represents a deviation from the desired timber colour and it is consequently of great interest to foresters to have the ability to predict the occurrence of discoloration in standing trees (Wernsdörfer et al. 2005). According to Knoke and Schulz Wenderoth (2001) trees with a high average diameter growth rate were less likely to have discoloration. They named age and diameter as factors that increase the probability of discoloration. Furthermore, discoloration can be initiated by e.g., oxygen entering through dead branches, branch scars, damages and wounds, or forks (Wernsdörfer et al. 2005). In this study, branches may have influenced the occurrence of discoloration in the investigated European beech trees, since discoloration surface was significantly related to competition intensity: No higher discoloration surfaces (> 10.0 %) were observed with higher competitive pressure (> 1.5). As dead branches or branch scars may lead to entering oxygen and thus an initiation of discoloration in European beech, high competition might have reduced this initiation for the investigated sample trees. These concords with the observed relationship between the number of bark anomalies and discoloration surface: the higher the number of bark anomalies, the higher the discoloration surface. However, the relationship between discoloration surface and competition intensity was rather weak. It might rather be related to the fact that highest discoloration surfaces were observed for sample European beech trees in mixture with noble hardwoods (ash and maple), which were only of lower competitive pressure to these sample trees. These sample trees were additionally the oldest and thickest sample trees. Both, age and DBH are considered to foster the initiation of discoloration in European beech trees (Knoke and Schulz Wenderoth 2001; Knoke 2003). Here, age and DBH were significantly correlated to discoloration surface (Table 3.4, p. 80). Therefore, competition intensity might rather tend to be a driver for branchiness and knottiness than for discoloration. The observed relationship between the bark anomalies and discoloration may more likely be due to larger bark irregularities such as greater wounds rather than branches or branch scars. Discoloration appears to depend more on age and diameter than on competition intensity. As stated by Wernsdörfer et al. (2005), assessing discoloration in standing trees based on external features appears difficult. Nevertheless, age, diameter, and external wounds seem to help to estimate the probability for discoloration in European beech trees.

Furthermore, it was found that a quality assessment with terrestrial laser scanning as well as by trained forest personnel can reliably predict the internal timber quality based on external quality features. There were significant correlations between the quality assessment at the standing tree performed by local district foresters according to RVR guidelines (RVR 2014): Sample trees graded in quality grade B had a lower internal knot surface, sample trees graded in quality grade C had a higher discoloration surface. Here external timber quality characteristics such as branches, branch scars, wounds, necrosis, or spiral grain led to a classification to a lower quality grade which could be validated by the internal quality assessment. The same was observed by Sterba et al. (2006). In addition, the quality assessment using TLS, expressed in the number of bark anomalies, significantly correlated with the internal discoloration surface. This indicates that trees classified in quality class C had external quality features that indicated affected internal quality. These features could be branches, branch scars, bumps, or necrosis. However, since there was no correlation between the bark anomalies and the inner knot surface, larger wounds appear to be the driving factor here. Especially as the discoloration surface also increases with an increasing number of bark anomalies. Conversely, this means that the higher the competition, the fewer the branches, the higher the amount of quality class B. The lower the competition, the larger the bark defects or bark irregularities, the higher the amount of quality grade C, the higher the probability of discoloration. However, this is strongly dependent on the age and diameter of the sample tree. Although neighbourhood species identity seemed to be of lesser influence on discolouration, it was difficult to disentangle the influence of neighbourhood species identity on discolouration from other influences such as site conditions or competition intensity.

5.3. Mixed versus pure forest stands

In recent decades, pure coniferous forests have been converted into mixed forest stands (e.g., von Lüpke et al. 2004; Bravo-Oviedo et al. 2014). Mixed forest stands are commonly assumed to be more resistant and resilient towards natural hazards and changing climate conditions, may promote biodiversity, can enhance productivity, and might economically be more stable (von Lüpke et al. 2004; Millar et al. 2007; Vilà et al. 2007; Knoke et al. 2008; Knoke and Seifert 2008; Pretzsch et al. 2015; Bauhus et al. 2017a; Ammer 2019). Also, stand structural complexity may be increased in mixed compared to pure coniferous forest stands (Juchheim et al. 2019). However, increasing structural complexity in mixed stands can lead to more heterogeneous growing conditions. Heterogeneous growing conditions imply variations in growth patterns, differing morphologies, and a different habitus of the involved tree species (Pretzsch and Rais 2016). The crown ratio, crown projection, or crown plasticity can be affected by tree species mixing and thus higher branchiness can occur (Seidel et al. 2011a; Bayer et al. 2013; Pretzsch and Rais 2016; Benneter et al. 2018). Hence, stem and crown form, taper, stem bending or straightness may be more variable (Pretzsch and Rais 2016; Bauhus et al. 2017b). Also the number of branches, branch dimensions but also internal timber characteristics like wood density may be affected by higher structural heterogeneity (Bayer et al. 2013; Zeller et al. 2017). As the conversion of pure forests to mixed forest stands is a major objective of forest management in several countries of the world (FAO 2001; von Lüpke et al. 2004; Forest Europe

2015; BMEL 2018), the questions arises as to how different tree species mixtures affect timber quality of a predominant tree species for forest conversion, European beech (Ammer et al. 2008; Rumpf and Petersen 2008). Comparing pure European beech stands with mixed European beech stands revealed that tree species mixing resulted in a tendency towards reduced timber quality in terms of higher knot surfaces in mixed forest stands. This agrees with e.g., Benneter et al. (2018), who also observed lowered stem quality in more diverse forest stands. The knot surface, for example, might be differently influenced in pure and mixed forest stands. Mixed forest stands are structurally more heterogeneous which results in varying light conditions (Pretzsch and Rais 2016). A higher light availability can e.g., lead to greater crown dimensions, to more or thicker branches (Mäkinen 2002; Mäkinen and Hein 2006) and consequently to an increased internal knot surface. Additionally, a higher light availability can also lead to higher stem taper or slenderness, but also to an increased diameter increment (Ammer 2003; Sevillano et al. 2016) and thus a greater tree ring width (Pretzsch and Rais 2016; Richter 2019). Zeller et al. (2017) showed that tree ring width and tree ring density were affected by tree species mixing with lower tree ring wood density in mixed compared to pure forest stands. Wood density is considered to be one of the most important parameters of wood quality due to its correlations to mechanical properties (Niklas and Spatz 2010; Diaconu et al. 2016). While for coniferous tree species (e.g., Norway spruce) a higher tree ring width is associated with lower wood density, this relationship is rather weak for the diffuse-porous tree species European beech (Diaconu et al. 2016). A higher structural heterogeneity through tree species mixing can therefore either increase or decrease timber quality. On the one hand, this strongly depends on the investigated quality criterion, the admixed tree species, their ecological requirements, their growth potential, as well as competitive ability (Benneter et al. 2018). On the other hand, it depends on forest stand properties and on the intended usage of trees or tree species. Admixed tree species may also serve as trainer trees in order to improve the quality of economically important tree species of forest stands (Bauhus et al. 2017b). Shade-tolerant subdominant tree species can thus cause beneficial effects such as shading of the lowest and most valuable stem section which will in turn foster natural pruning and prevent the initiation of epicormic branches (Bauhus et al. 2017b).

Given the changing and uncertain climate conditions as well as an increased frequency of natural hazards, a mixture of tree species is in any case important for the ecological and economic stability of forests. European beech may also be vulnerable to extreme weather events. Barna and Mihál (2019) argued that beech bark disease complex in Central Europe is influenced and initiated by climatic extremes. As these climatic extremes will occur more frequently in the future and also other tree species may be affected by pathogens, mixed stands and the resulting increased stability of the forests will become very important. Since a heterogeneous stand structure of mixed forest stands can have both advantages and disadvantages for the quality of mixed tree species, it will become important to optimally use the effects on the different tree species. In this way, both intra- and interspecific competitive effects can be beneficial and timber quality can be improved.

5.4. Methodological considerations

The comparative investigation on the influence of intra- and interspecific competition on timber quality of European beech trees was introduced as the main research questions of this thesis. However, there are several aspects that might have substantially influenced the results on this research question and may have reduced the explanatory power.

First of all, wood has a rather long production cycle, which lasts for generations and is accompanied by a variety of silvicultural measures (e.g., thinning, harvesting operations) or other processes (e.g., self-pruning, damages) (Benneter et al. 2018). However, this means that the current quality of a tree is based on its past. Since all investigated sample trees originated from commercial forests and have experienced a history of silvicultural measures, the current competitive situation might only explain a small part of the observed quality of the trees. Here, the influence of former silvicultural management but also of other processes (natural pruning, damages) cannot be excluded. Moreover, there are many ways to measure and describe the competitive situation of a tree. Here, Hegyi's index of competition was used. This index is based on DBH and on the distance between a target tree and its neighbouring trees (Hegyi 1974). Other competition indices also take species-specific features such as tree height, crown dimensions and form, or light conditions into account, can hence capture certain competition mechanisms and might better disentangle species effects on quality. Hegyi's index, however, only reflects some aspects of competition, namely DBH and distance, while not accounting for the above-mentioned species-specific features. Hegyi's index does not differentiate between species effects, as it is only a measure of competition intensity, regardless of the species causing it. It is therefore only of limited help when species-specific effects are to be addressed. Furthermore, the mixed forest study sites contained high proportions of European beech trees, with the result that there were barely any solely interspecific competitive situations. This could explain difficulties when trying to disentangle species effects and may further have caused overlapping effects of intra- and interspecific competition. Also, the influence of soil and climate conditions, light, nutrient, and water availability, but also of genetic predisposition on timber quality were not included in this study and remain unclear. Lastly, all of the sample trees were graded as "average" or relatively "good" quality (quality grades B and C according to RVR grading guidelines, RVR 2014), since the sample trees originated from commercial forests with quality supporting thinning operations. A wider range of trees graded as "excellent", "medium", and "poor" quality might have led to more contrasting results. One might also argue that these small values and differences are not relevant for further processing. Here, it depends on the final purpose of the timber. Quality is defined by consumers and thus by the end of the production chain. It remains that, depending on the quality class, a single knot could still downgrades an entire log (according to European grading standards, Deutsches Institut für Normung e. V. 2011; Deutsches Institut für Normung e. V. 2013) due to its effects on the mechanical, physical and aesthetic properties of the wood (Torkaman et al. 2018). Quality is and will remain dependent on the intended usage.

There are additionally considerations regarding the applied techniques. While a quality assessment using TLS can be recommended (e.g., due to the transferability of the methods to mobile laser scanning and the associated reduces workload in the field), the manual measurement of quality features from photographs with the software Datinf® Measure has proven to be very time and labour intensive. This method is only recommended if an automated measurement can be performed.

5.5. Conclusions and outlook

In conclusion, the results of the three presented studies showed that competition intensity affects external and internal timber quality characteristics of European beech (research question 1). This effect seemed to be stronger than the effect of neighbourhood species identity, as a tendency towards increased quality was observed in pure beech stands under highest competitive pressure (research question 1 and 2). However, the measured quality values and the observed differences were only small. A study including a wider range of quality grades and of competitive pressure might have resulted in more than a tendency. Furthermore, including the competitive situation at different growth stages would have strengthen the influences on the initiation of timber quality characteristics. Moreover, the results have shown that external timber quality can be derived *in-situ* through terrestrial laser scanning (research question 1) as well as by trained forest personnel. A quality assessment at the standing tree may help to estimate the internal timber quality because the external quality features were in accordance with the internal quality features (research question 3). Usually, the external and internal timber quality are only examined separately. In this study, however, the entire chain was investigated. This highlights the scientific research contribution of this work. It has been shown that it is possible to estimate the internal quality using external quality characteristics for European beech - both by trained personnel and by terrestrial laser scanning. Here, terrestrial laser scanning could be a valuable addition in the future, since an objective and quantitative external quality assessment of the standing tree up to crown base height was enabled. The approach developed here can also be transferred to other tree species (Burkardt et al. 2019). Considering research question 4, better qualities in terms of lower knot surfaces were observed for sawn boards in the lower stem section as well as for the outer boards. This might be a precious information for the wood processing industry to optimise the sawing procedure through log positioning and individual sawing patterns. However, the measured values for the quality features were small and it can be argued that knot surfaces this small do not have such a major impact on timber utilisation. In summary, the results have demonstrated that mixed forest stands may come at the expense of timber quality in terms of higher knot surfaces in mixed forest stands (research question 5). However, the numerous advantages of mixed forest stands (e.g., resistance, resilience and stability in changing an uncertain climate conditions) remain of increasing importance. For example, admixing beech to spruce can mitigate a climate related growth loss of spruce at certain site conditions (Pretzsch et al. 2010). Understanding which tree species are beneficial to each other or have a beneficial impact on quality allows optimal use of complementary and competitive effects. Including intraspecific effects in mixed forests could further promote the quality of individual tree species. Mixed forest stands still present many benefits (Knoke et al. 2008) and can better fulfill several ecosystem services. In conclusion, the question remains of what will be produced from the timber. Does volume have priority over quality or vice versa? Will engineered wood products be produced so that negative effects of knots or other quality-reducing features can be mitigated? Can knots or discoloration be advantageous for aesthetic reasons? In the end, the consumer determines quality. It therefore depends on which forest-management goal should be achieved and in what way.

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Declaration of honor

I, Kirsten Höwler, hereby declare that I am the sole author of this dissertation entitled "Influence of intra- and interspecific competition on timber quality of European beech" and that all references and data sources that were used in this dissertation have been identified as such.

I further declare that this thesis has never been submitted in any form as part of any other dissertation procedure.

Kirsten Höwler

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