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Tree species diversity does not compromise stem quality in major European forest types

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A B S T R A C T

Mixed-species forests can have higher productivity, in terms of wood volume, than monospecific forests. In addition, higher tree species richness has been found to positively correlate with multiple ecosystem services and functions. Surprisingly, stem quality as one of the most important factors regarding the economic value of forests has rarely been formally studied in diverse forests. This paper aims at investigating how tree species richness influences stem quality and which factors may drive quality development in these stands. Stem quality, understood here essentially as the suitability of a particular stem for particular end-uses, is influenced by a tree's ability to capture sufficient resources for growth and is influenced by neighbouring trees, e.g. through shading and physical crown interactions. We collected data on crown size, stem form and tree health for over 12,000 trees in 209 study plots in six European regions (Finland, Germany, Poland, Romania, Italy and Spain) within naturally diverse forests to assess the impact of tree species richness on these characteristics. Results showed that quality variability between regions, stands and individual trees was high across species. At the stand level, there was a slight tendency towards lower stem quality with increasing diversity. However, individual trees of high quality were present at all diversity levels and for all target species. Tree species richness could not be confirmed as a primary influence on stem quality at the stand level. Rather, stand and individual tree properties such as structural composition, competition, tree size and crown characteristics were identified as the main factors for stem quality development, even in mixed stands. Many of the factors identified in this study can be directly or indirectly influenced by forest management strategies tailored to produce high-quality timber in mixed-species forests. Our findings suggest that diverse stands are not inferior regarding stem quality, while at the same time being able to provide various other ecosystem services.

1. Introduction

There is now a large body of evidence that tree species diversity has in most cases a positive influence on the biomass productivity of forest ecosystems (Bauhus et al., 2017; Forrester and Bauhus, 2016; Liang et al., 2016; Paquette and Messier, 2011; Pretzsch et al., 2015; Ruiz-Benito et al., 2014; Vilà et al., 2013). Tree species diversity may also enhance the provision of other ecosystem services, such as water purification, air cleansing and oxygen provision, soil development and retention, regional climate regulation and carbon sequestration (Cardinale et al., 2011; Gamfeldt et al., 2013; Noss, 2001; Ozanne et al., 2003; Ruiz-Jaen and Potvin, 2011). Surprisingly though, the main interest of many forest owners *besides* biomass productivity – namely the commercial value of forest production – has remained largely unaddressed in biodiversity research in forests (Knoke, 2008). While the other mentioned ecosystem services may have economic relevance, they cannot be marketed unless some ethical and structural issues can be resolved. Presently, the marketing of only these services does not offer promising economic opportunities for most forest owners (Muradian et al., 2013). Until they do, the prime direct economic function of forests is based on the production of wood. Consequently, if forest owners are to adopt management systems comprising higher tree species diversity, they must be convinced that this improves not only societal values but also their income and the economic value of their forests. If tree species diversity can enhance biomass productivity, forest owners and managers producing timber for low-value end-uses, such as pulp and paper, fibre boards and fuel certainly can profit from managing for higher diversity. But while these products make up a large

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portion of the total wood consumption, profitable forest management depends on production of high quality timber in many parts of the world. Therefore, biomass productivity alone is not sufficient for economic valuation of most forests. Market prices of logs for high-revenue end-uses, such as appearance-grade lumber and veneer, depend strongly on the quality of the raw material – timber. Forest owners will thus only be willing to manage forests with higher tree species diversity, if this improves, or at least does not compromise, the production of high quality timber.

One might argue, that unlike quantity, quality "lies in the eye of the beholder", or in the case of timber, is determined by the motives of the utiliser of the final wood product. It has therefore been proposed to define timber quality according to its intended end-use (see for example van Leeuwen et al. 2011). For the timber provider, however, two problems arise from this approach.

Firstly, it is difficult to find one single measure to satisfy the information need about the quality of the resulting roundwood log, let alone that of the lumber, as long as the tree is still standing.

While it would be ideal to know the intrinsic properties of the resulting roundwood or lumber products while trees are still standing, these properties are costly and onerous to study, because sampling is in most cases destructive. It is hence necessary to already gain a reasonable insight about the quality of trees and stands even when the final harvest is decades away. Therefore, forest managers must rely on extrinsic, or external, quality assessment proxies to decide about the retention or the removal of trees during management operations.

Secondly, even if all information was available before the trees were harvested, limiting the production of a given stand to only one end-use can be risky and problematic, even in plantations, where this has historically been considered less of a problem (Kelty, 2006; Piotto et al., 2010). Therefore, managers must operate with a grading system that provides them with some flexibility in terms of end-uses. A stem with prospective veneer-quality (typically the highest quality grade) can be used for a cascade of lower-grade end-uses if its quality deteriorates over time.

These external stem properties are indicated by the presence of branches, knots, branch wounds and stem deformations, curvature, taper, epicormic branching, and defects caused by mechanical damage, irregular growth, pests and pathogens (Dănescu et al., 2015; Larson, 1963; Mäkinen, 1999; Thies et al., 2004). Many of these properties may be influenced by the tree species composition of stands. In mixed stands, for example, branchiness may be increased, because trees of different species often exhibit different light transmission (Dong et al., 2016; Medhurst et al., 2003). This can lead to certain trees developing more branches in spaces with higher irradiation (Forrester et al., 2012).

Even though stem quality, as judged by these external variables, is not linearly related to roundwood and lumber quality, a tree with high stem quality is more likely to yield roundwood and sawnwood of high quality than one with low stem quality (Sterba et al., 2006).

In order to provide an effective assessment scheme, stem quality in forestry has been traditionally defined using classes such as A, B, C, D grade (e.g. European Commission, 1997, 2008), especially for hardwoods. These allow the timber provider a relatively simple allotment of the timber and give prospective buyers a reasonably accurate prediction of the degree to which the timber fulfils certain wood property requirements by specifying thresholds for stem defects (i.e. deviations from the properties of a log considered nearly flawless, or of grade A). The differences in economic terms between these classes can be considerable (see for example Supporting Information S1-1, Table S1-1).

In forestry, knowledge about the effect of tree species interactions on timber quality is largely restricted to specific mixtures in which at least one species is used to facilitate quality development in at least one other species, for example the facilitation of self-pruning on the lower stem of valuable hardwoods through subdominant shade-tolerant species (Burschel and Huss, 1997; Kramer, 1988; Röhle, 1984; Saha et al., 2014; von Lüpke, 1998). In contrast, the development of timber quality in even-aged monocultures has been intensively studied for many commercially important species (e.g. Erickson and Harrison, 1974; Medhurst et al., 2011; von Lüpke, 1998; Zobel, 1984). Yet, there is very little general information on timber quality in mixed-species stands (Bauhus et al., 2009, 2017). Mixtures tend to provide more heterogeneous growing conditions owing to differing growth dynamics, morphology, and ecological adaptations of the participating species (Pretzsch and Rais, 2016). This structural heterogeneity may increase the variability in stem and crown properties such as taper, straightness or stem and crown form regularity of all or some species in the mixture (Jucker et al., 2015; Pretzsch, 2006).

Mixtures of species with differing crown architecture and apical dominance may also exhibit more curved and leaning trees, if one species is forced to grow into unoccupied or unshaded growing space to compete for light, exhibiting phototropic growth (Grotta et al., 2004), or if species with strongly different resistance to mechanical branch abrasion (Hajek et al., 2015; Putz et al., 1984) are mixed. This may also lead to irregular crown shapes and associated variable branch dimensions, where branches exposed to more light and growing space are longer and thicker (Kint et al., 2010). Differences in light transmittance between species may also promote epicormic branching in areas with higher light exposure compared to more homogeneous monospecific stands (Blum, 1963; Books and Tubbs, 1970; Takiya et al., 2010).

The competitive influences of the direct tree neighbourhood, along with the species-specific architectural traits and the site influences, shape the morphology and growth dynamics of a given target tree (Lang et al., 2010; Ratcliffe et al., 2015). Neighbourhood-level analyses, therefore, promise important insights into species diversity influences on stem quality. But while single-tree-based silvicultural approaches are gaining importance, especially in forests managed for multiple services and high stem quality, the stand level often remains the central scope for mid- and long-term planning, yield and revenue calculation and inventory and implementation assessment (Oliver and Larson, 1990; Pukkala, 2002). In addition, tree species diversity of forests and the degree and form of mixture, are commonly understood as stand-level variables by managers and their impact is often evaluated at that spatial scale (Kuuluvainen, 2009; Pretzsch and Schütze, 2009). Consequently, we analysed stem quality in this study at the level of the stand and aggregated important variables at the stand-level. While there is some knowledge on the effects of specific tree species interactions, there is no general information on how stem quality of trees may change with increasing tree species diversity (Bauhus et al., 2017). Therefore, our study addressed the hypotheses that:

(1) tree species richness affects crown and canopy characteristics, which are responsible for stem quality development, and
(2) the quality of tree stems is negatively related to tree species richness

To analyse the relationship between tree species diversity and stem quality, we used forest stands covering a wide range of tree species combinations in different climatic and vegetation zones across Europe.

2. Materials and methods

2.1. Study design

To study the effect of tree species diversity on stem quality, we used plots ranging in tree species richness from 1 to 5 species for a variety of combinations of European tree species from boreal to Mediterranean forest ecosystems. The study areas and plots were the same as used in the interdisciplinary project FunDivEurope (http://www.fundiveurope.eu/) (Baeten et al., 2013). The exploratory platform of this project offered a wide geographic and climatic range, and a pool of tree species representing Europe's economically most important species (see S1-3 in Supporting Information 1 for a full list of species, species compositions