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A quantitative comparison of the structural complexity of managed, lately unmanaged and primary European beech (*Fagus sylvatica* L.) forests

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ABSTRACT

The high structural heterogeneity of primary forests is assumed to positively affect various ecosystem traits and functions, e.g. biodiversity, resilience and adaptability. Against this background, old-growth forest structures are emulated in many managed forests. To properly emulate such structures, quantitative reference values are required, through which primary forests are characterized. In this study, we used the stand structural complexity index (SSCI), derived from terrestrial laser scanning (TLS), to characterize and compare the structures in European beech (*Fagus sylvatica* L.) dominated forests along a management gradient, ranging from differently managed stands, over formerly managed but now unmanaged stands to primary forests, which have never been managed. The study objective was to quantify and compare the structural complexity of these forests to give insight into possible reference points for an improved prospective handling of managed forests. The highest stand structural complexity was found in primary forests. While there were no significant structural differences between the managed forests, they were more complex in structure than formerly managed forests that have been set aside as National Parks now. The results also showed that structural complexity significantly differed between the investigated stand age classes. Next to primary forests, thickets growing below sheltering overstory trees in managed forests resulted in high structural complexity values. The findings suggest that specific silvicultural management practices can increase the structural complexity in beech forests. This study may facilitate a 'management for complexity' in silvicultural practice and might lead the way towards a more precise promotion of three dimensional forest structures that are associated with specific forest functions as part of the stand management objectives.

1. Introduction

An essential part of modern silviculture is emulating natural forest dynamics and structures as found in primary forests, while sustainably producing timber and maintaining the site productivity (Gustafsson et al., 2012; Nagel et al., 2013). In order to be able to imitate natural dynamics and structures in managed forests as much as possible, primary forests as reference systems need to be studied and their structural characteristics need to be quantified (Brang, 2005; Nagel and Svoboda, 2008; Feldmann et al., 2018a; Nagel et al., 2013). Under the current climate conditions, European beech (*Fagus sylvatica* L.) is one of the most important climax species in unmanaged forest ecosystems across Central Europe (Ellenberg and Leuschner, 2010). However, only a few of such beech dominated primary forests could be preserved until today (Kucbel et al., 2012; Trotsiuk et al., 2012; Hobi et al., 2015; Glatthorn et al., 2017).

Korpel' (1995) and Tabaku (1999) described the natural dynamics of these primary forests by a developmental cycle, which mainly consists of three phases: the growth phase, the optimum phase and the decay phase. In the literature, other terms are used often: initial or establishment phase instead of growth phase, and terminal phase instead of decay phase (Feldmann et al., 2018b; Winter and Brambach, 2011; Zenner et al., 2016). These phases can function as points of reference to characterize a specific forest structure, but they also tend to simplify the complexity of such structures. Natural disturbances can interrupt the developmental cycle at any time and reset the cycle. This can happen at small or quite large scales and depends on the type and intensity of the disturbance. Such disturbances are integrated parts of

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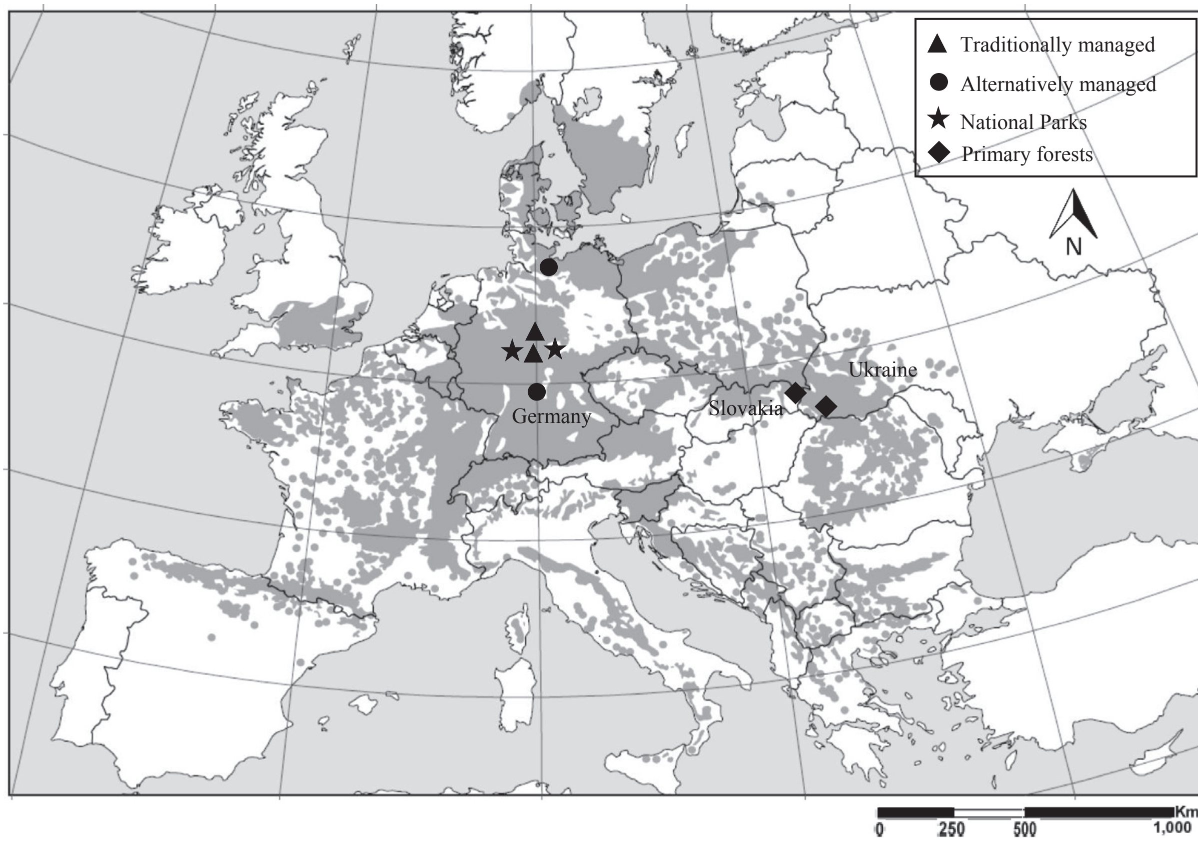

Fig. 1. Distribution pattern (grey) of European beech (*Fagus sylvatica* L.) in Europe according to EUFORGEN (2009) and geographic locations of the eight study areas.

the complex natural forest development (Nagel et al., 2006; Feldmann et al., 2018a; Scherzinger, 1996; Trotsiuk et al., 2012) and result in the high heterogeneity found in these primary forests.

One developmental phase usually not present in managed beech forests is a large-scale decay phase. In primary forests, European beech trees can reach an age of 400–500 years (Trotsiuk et al., 2012). In managed stands, the rotation period for beech usually lies around 120–140 years in Central Europe. Management hence prevents the beech trees from reaching their natural age limit (Bauhus et al., 2009; Boncina, 2000; Scherzinger, 1996). Consequently, many of the characteristics and attributes commonly associated with old-growth forests, like large numbers of dead or dying trees, veteran trees or high amounts of downed dead wood are mainly absent in managed stands (Bauhus et al., 2009; Meyer, 2005; Paffetti et al., 2012; Nagel et al., 2013). However, these attributes are significant structural elements affecting the three-dimensional forest appearance.

Structural dynamics in primary European beech forests are mainly driven by small-scale disturbances (Hobi et al., 2015; Nagel and Svoboda, 2008; Feldmann et al., 2018a; Nagel et al., 2013; Trotsiuk et al., 2012). The main abiotic disturbance factors in European beech forests are storm events, which result in crown and tree damages or windthrow at different spatial scales (Jaloviar et al., 2017). Especially senescent or already damaged trees are susceptible towards wind. While larger canopy gaps either lead to an increased development or growth of lower canopy layers (vertical ingrowth), smaller canopy gaps are closed again through the horizontal canopy expansion of neighboring trees (Feldmann et al., 2018a; Pretzsch and Schütze, 2005).

Despite recent findings reporting intermediate and also large-scale disturbances of several hectares in primary European beech forests (e.g. Nagel et al., 2006; Jaloviar et al., 2017; Feldmann et al., 2018a; Trotsiuk et al., 2012), the central European silvicultural approach for European beech still focusses mainly on mimicking small-scale disturbances by removing single trees or small tree groups, which either emulates self-thinning through competition or the phase of natural decay (Feldmann et al., 2018a). This approach aims at increasing the heterogeneity of forest structure and thereby promoting important ecosystem properties such as resistance and resilience (Knoke and Seifert, 2008; Messier and Puettmann, 2011; Pommerening, 2002), as well as functions and services such as biodiversity (Brang, 2005; Gustafsson et al., 2012; Pommerening, 2002, but see Schall et al. (2018a) for contrasting findings), productivity (Glatthorn et al., 2017; Juchheim et al., 2017), and microclimatic stability (Messier and Puettmann, 2011; Ehbrecht et al., 2017) and other features of multi-functional forests (Gadow et al., 2012).

To successfully create such heterogeneous structures, they need to be measurable and reproducible in the first place. A conventional method to do this is measuring tree-based attributes, which are used to draw conclusions about the structure of the whole stand (Pommerening, 2002; Schall et al., 2018b). Apart from conventional measures, terrestrial laser scanning (TLS) allows for a detailed quantification of stand structural complexity based on three-dimensional point clouds that reproduce the spatial arrangement of objects in a given forest scene with great detail. Such point clouds allow analyzing and comparing forest structures, e.g. across different management intensities and management types (Seidel et al., 2016; Ehbrecht et al., 2017).

For European beech forests, it is unknown so far how the structure derived from three-dimensional point clouds differs among differently aged forests, differently managed forests, lately unmanaged forests and primary forests. In this study, we applied a recently suggested TLS-based measure of structural complexity to investigate the structural properties of differently managed, lately unmanaged and completely unmanaged European beech forests in Germany, Slovakia and the Ukraine, including Europe's last primeval beech forests. We hypothesized that (i) structural complexity increases with decreasing management activity, and that (ii) significant differences in stand structure exist between different age classes, but high levels of structural complexity are not only limited to older stand ages.