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# Effects of forest management on stand leaf area: Comparing beech production and primeval forests in Slovakia

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ABSTRACT

The productivity and water consumption of forests depend on stand leaf area, which may vary with tree age, forest structure, and environment. How forest management affects leaf area and whether production forests have different leaf areas than unmanaged natural forests, is not clear. We compared the leaf area index (LAI) of production forests of European beech (*Fagus sylvatica*) with that of primeval forests (three forests in each case) in Slovakia and analyzed the LAI change from early to late stages of the natural forest development cycle. Optically determined LAI (LAI2000 Plant Canopy Analyzer) was on average 7.1 $m^2\ m^{-2}$ (2.8–11.0 $m^2\ m^{-2}$) in the primeval forests and 7.4 $m^2\ m^{-2}$ (4.3–11.2 $m^2\ m^{-2}$) in the production forests. Model results show that transforming beech primeval forests into even-aged production forests would reduce LAI by ~1.6 units, if stem density is kept constant. Complex primeval forest canopies thus promote the formation of higher LAIs. However, this effect was compensated for by the higher stem densities of the production forests, resulting on average in similar LAIs of production and primeval forests. In the terminal stage of natural forest development with tree death and gap formation, plot-level LAI was not lower than in the earlier growth and optimal stages, probably because neighboring beech trees were rapidly filling gaps with foliage. This suggests that stand-level productivity is not reduced in the terminal stage of forest development, since LAI is rapidly restored after the death of individual trees. Our results provide insights into the functional role of structural complexity in temperate forest canopies and how European beech maintains dominance across the full forest development cycle.

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## 1. Introduction

Leaf area is the surface through which plants exchange most energy, $CO_2$, and water vapor with the environment. The productivity of plant communities and their water loss are closely linked to stand leaf area, typically measured as leaf area index (LAI), i.e., the projected one-sided leaf area per unit ground area. Carbon assimilation and biogeochemical fluxes depend not only on leaf area but also on the spatial arrangement of the foliage in canopy space. This is especially the case in forests with their large canopy volume, where light intensity steeply decreases from canopy top to bottom.

It has been recognized that forest canopy structure and the associated leaf area index vary with tree species, tree age, and forest management regime (e.g. Bequet et al., 2011; Davi et al., 2008; Derose and Seymour, 2010; Gonzalez-Benecke et al., 2012; Le Dantec et al., 2000), but the relationship is not precisely known. Deeper understanding of these relationships is crucial for predicting productivity, water consumption, and forest dynamics under changing climatic conditions and altered forest management.

About 30 percent of the forest area on earth is managed with conventional silvicultural systems, which typically lead to single-layered, even-aged stands (FAO, 2010; Puettmann et al., 2015). Alternative management concepts with a focus on ecosystem services other than timber production have been developed and are receiving increasing attention (Puettmann et al., 2015). Several of these concepts promote the creation of more complex canopies, avoiding structurally simple even-aged stands. To advance this development, knowledge about the effects of management on forest canopy structure is mandatory. In production forests (commercially managed and logged forests), final harvest usually takes place at a time when the rate of timber accumulation decreases. In this phase, stand development is still far from the stage of tree senescence, where dying trees create gaps, structural diversity

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greatly increases, and deadwood accumulates (Drössler and Meyer, 2006; Oliver and Larson, 1996).

Most knowledge about the canopy structure and leaf area of forests has been collected in production forests during the initial and growth stages of stand development, while not much is known about old-growth or primeval forests without management impact. In particular, there is poor understanding of the complex canopy structure of the terminal stage of forest development, when individual trees or groups of trees die of age.

European beech (*Fagus sylvatica* L.) is the most important tree species of Central European natural forest vegetation (Bohn et al., 2003) and it is also one of the economically most valuable timber species. Across its distribution range, beech dominates many forest communities in particular on acid soils, forming quasi-monocultures due to its high competitive strength (Leuschner, 2015). A characteristic of this typical late-successional species is its extended shade crown, which reduces light transmission to the ground to 1–2% of incident light or less (Leuschner and Ellenberg, 2017; Mayer et al., 2002). This is achieved by several layers of highly shade-tolerant leaves aligned horizontally in the lower part of the crown. How this complex canopy architecture changes with tree age and responds to management interventions is best studied by comparing beech primeval forests with production forests.

We studied canopy light transmission and gap fraction in three Slovakian beech primeval forests with no management impact for the past several hundred years and compared these old-growth forests to nearby beech production forests shortly before harvest. Based on measurement campaigns with the LAI2000 Plant Canopy Analyzer at two height levels in the stand, we derived the effective leaf area index $LAI_e$ and its spatial variation across different development stages in the primeval forests and the mature production forests. Since optical LAI data typically represent underestimates of true leaf area, we compared our $LAI_e$ means with the results of a litter trapping study in the same stands, which may give more reliable stand-level averages, while the assignment of these leaf area data to individual plots or forest development stages is difficult.

The objectives of the study were (i) to quantify differences between primeval and production forests in leaf area and its spatial distribution and (ii) to explore changes in $LAI_e$ across the development stages of a forest development cycle. We tested the hypotheses that the horizontal distribution of foliage is more heterogeneous in the primeval forest canopy and that the multi-layered structure results in a larger leaf area than in the production forests. Our assessment of canopy structural diversity through optical and biomass-related measurements on a large number of plots represents an alternative to the classical approach of canopy analysis with a focus on stem position, tree size, and crown projection area (von Gadow et al., 2012; Pommerening, 2002).

## 2. Methods

### 2.1. Study region and investigated stands

Three beech primeval forests at montane elevation (550–950 m a.s.l.) in the Western Carpathians in eastern Slovakia (48°01′–49°08′N, 22°01′–22°54′E) were studied. They are part of the forest reserves Havešová, Stužica (both inside Poloniny National Park), and Kyjov in the Vihorlat mountains, which belong to the UNESCO World Heritage Site "Primeval Beech Forests of the Carpathians and the Ancient Beech Forests of Germany" (Table 1). The forests are true primeval forests with no human intervention for the past several hundred years (Korpeĺ, 1995). However, the sites have been influenced by atmospheric deposition of nitrogen, acids, and other anthropogenic substances since the beginning of industrialization in a similar manner to many other woodland regions in the industrialized regions of the world.

Three production forests were selected at similar elevation and within a distance of 1 km to the primeval forests for comparative study. The selected stands were managed in a shelterwood cutting system with two subsequent cuts within 10 years at the end of the production cycle. This system is the most widespread beech forest management regime in Slovakia and is practiced in strips parallel to the slope, structuring the production forest in longitudinal sections of beech cohorts of similar age and relatively high stem density, as the stands are normally thinned only about 10 years before final harvest (Green Report, 2009; Marušák, 2007). The rotation period is in most cases relatively short (typically 80–100 years) with the consequence that more than 90% of the Slovakian beech production forests are less than 100 years old (National Forest Centre, 2009).

While the primeval and managed stands had similar total basal areas (32–43 $m^2\ ha^{-1}$), stem density in Havešová and Stužica was markedly higher in the managed than in the primeval forests. Except for Kyjov, the quadratic mean stem diameter and dominant height were lower in the production forests (Table 2). All six forests belong to the Fagetum dentarietosum glandulosae community (Bohn et al., 2003), with presence of a larger number of acidity-indicating species in the Kyjov stands on Dystric Cambisols. The canopy of the primeval forests in Havešová and Kyjov consisted nearly entirely of *F. sylvatica* (except for a few *Acer pseudoplatanus* L., *Acer platanoides* L. and *Fraxinus excelsior* L. trees), whereas the Stužica forest contained about 10% *Abies alba* Mill. at elevations >1000 m a.s.l. In the production forest of Kyjov about 94% of the canopy trees were beech. The production forests of Stužica and Havešová had higher proportions (23 and 39%) of *A. platanoides*, *A. pseudoplatanus*, *F. excelsior* and other broad-leaved tree species. The beech trees in the primeval forests reached maximum ages of up to 400 years (R. Coventry, unpublished), while the trees in the production forests were cohorts of relatively similar age (ca. 90–100 years in Kyjov and Stužica and ca. 70 years in Havešová). The production forests were close to final harvest and thus had reached their maximum biomass in the production cycle.

### 2.2. Study design

To analyze changes in canopy structure throughout the forest development cycle, research plots were first selected in each of the primeval forests and assigned to one of the three following main development stages: growth, optimal or terminal stage. A regular grid was placed in each of the three primeval forests and 40 circular plots of 500 $m^2$ size (25.24 m in diameter) were established on the grid nodes. Grid spacing was chosen so that the 40 plots were located within the reserves and no plot was within 100 m distance to the nearest reserve border. In the plots, basic stand structural parameters were recorded and used to assign each plot to one of the development stages (see below). Four plots per development stage and primeval forest were then selected for an in-depth analysis of canopy structure.

The production forests were smaller-sized than the primeval forests, therefore ten plots were selected in each and inventoried in the same manner as in the primeval forest plots. Again, four of the ten plots were selected for the analysis of canopy structure. This stratified random sampling approach ensured a precise quantification of basic stand structural parameters in all six forests and a balanced study design with equal representation of all development stages in the dataset for the analysis of canopy structure.

Basic stand structural parameters were recorded in 150 plots in total: 40 plots per primeval forest and 10 plots per production forest. The in-depth canopy analysis was conducted in a subset of 48

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