Using close range remote sensing and radiative transfer modelling to assess the competition for light in European beech forests

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Introduction

Understanding the dynamics of carbon sequestration and productivity of forest ecosystems is crucial for addressing global environmental challenges and ensuring the sustainable management of forests. To accurately model and predict these processes, it is essential to comprehend how trees grow and identify the factors that limit their growth. Important growth limiting factors include site and climatic conditions, disturbing extreme events, the availability of vital resources, and competition among trees for these resources. The competition for different resources (e.g., water, nutrients, and light) collectively contributes to a cumulative competitive pressure on trees, which is often quantified using competition indices. Many competition indices aggregate the different aspects of competition indirectly by considering either stand density or the size and distance of neighbouring trees (Biging and Dobbertin 1995). However, research has provided initial evidence suggesting that the relative importance of distinct competition aspects as limiting factors for tree growth, varies depending on the social class of the tree (Seifert et al. 2014) and hydroclimatic conditions (Bennett et al. 2015; Chen et al. 2019). This highlights the importance of disentangling the different aspects of competition as distinct influencing factors to holistically understand their effects on tree growth.

The availability of light is one of the key aspects of competition that directly influences photosynthesis and overall tree productivity, making it a crucial driver of tree growth dynamics. Some studies have successfully separated the competition for light from the remaining competitive pressure summarized as "crowding" (Canham et al. 2004), presenting differing findings regarding which of the aspects had stronger influence on tree growth (Coates et al. 2009; Contreras et al. 2011; Fichtner et al. 2015). Notably, these studies rely on indirect assessments of competition aspects using indices, and research directly estimating and isolating the distinct aspects of competition remains scarce.

However, recent advances in technologies like Terrestrial Laser Scanning (TLS) and Radiative Transfer Models (RTMs) now allow direct estimations of one of the different competition aspects, the light availability as a result of shading by neighbours. In this way, the impact of light availability on tree growth can be examined separately from remaining competitive aspects, providing critical insights into how social classes and hydroclimatic conditions shape the importance of light and determine when it limits growth versus when other factors take precedence.

In this study, we aim to directly and precisely describe competition for light in European beech, the most common deciduous tree species in Europe, with considerable ecological and economical importance. We utilize 3D TLS data and the RTM "LESS" (Qi et al. 2019) to estimate the photosynthetically active radiation absorbed by individual trees. We combine this with basal area increment measurements in Linear Mixed Effects Models (LMEMs) to assess the link between light availability and radial growth. We aim to address the following research questions.

1. Is there a significant relationship between light availability and radial growth? Can the competition for light be separated from other competition aspects?
2. Which trees are light limited? Which roles do social classes and thinning play?
3. Under which hydroclimatic conditions is light availability more important than the remaining competition aspects?

Material and Methods

We analyse data from five sites in Baden-Wuerttemberg and Rhineland-Palatinate with different thinning regimes and about 900 sample trees. Tree growth is quantified using tree-ring widths from core samples, enabling the calculation of a five-year cumulative basal area increment (BAI_{5year}). Detailed 3D tree and stand structures are captured via TLS, with segmentation conducted through the R package CspStandSegmentation (Frey and Schindler 2024) and refined using Cloud Compare software (Girardeau-Montaut 2023). Competition indices, such as Hegyi's (Hegyi 1974) and KKL (Pretzsch H. 1992; Pretzsch 2009), are computed using the TreeCompR R package (Rieder et al. 2024) and later compared to the estimated light availability.

The light availability is estimated using LESS, a modelling framework that integrates detailed structural data, including tree crown shapes (from alpha shapes), stem shapes (represented as polygons, see (Frey et al.), and digital terrain and surface models of the site and region. LESS incorporates optical properties of leaves and stems alongside hourly solar angles to simulate absorbed photo-synthetically active radiation (APAR). Outputs include potential APAR ($APAR_{pot}$, excluding cloudiness) and actual APAR ($APAR_{act}$, accounting for cloudiness in wet and dry years), aggregated over the vegetation period.

To address our research questions, we fit statistical models using BAI_{5year} and annual BAI as response variables. Initial simple linear models assess the relationship between BAI_{5year} and $APAR_{pot}$. Subsequently, we employ LMEMs incorporating $APAR_{pot}$, competition indices, tree age, and social class as fixed effects, with tree IDs nested within sites as random effects. A final LMEM investigates BAI in relation to $APAR_{act}$ of specific years under different hydroclimatic contexts.

Expected Results

We expect to separate shading and crowding effects on tree growth, following Canham et al. (2004). As Seifert et al. (2014) observed for afro-temperate tree species, we anticipate that the relative importance of shading and crowding will vary based on tree social class. Dominated trees may rely more on light, while dominating trees are influenced by access to soil nutrients and water. We also hypothesize that hydroclimatic conditions will modulate the significance of light competition: in wet years, light availability may drive growth, while in dry years, water competition may be more critical. Excessive light in dry, hot conditions could even harm growth due to increased evapotranspirative stress (Bennett et al. 2015). These findings will help identify which trees are most limited by light under specific social classes and hydroclimatic conditions, providing a clearer understanding of the contexts in which light or other factors, such as water and nutrients, dominate growth constraints.

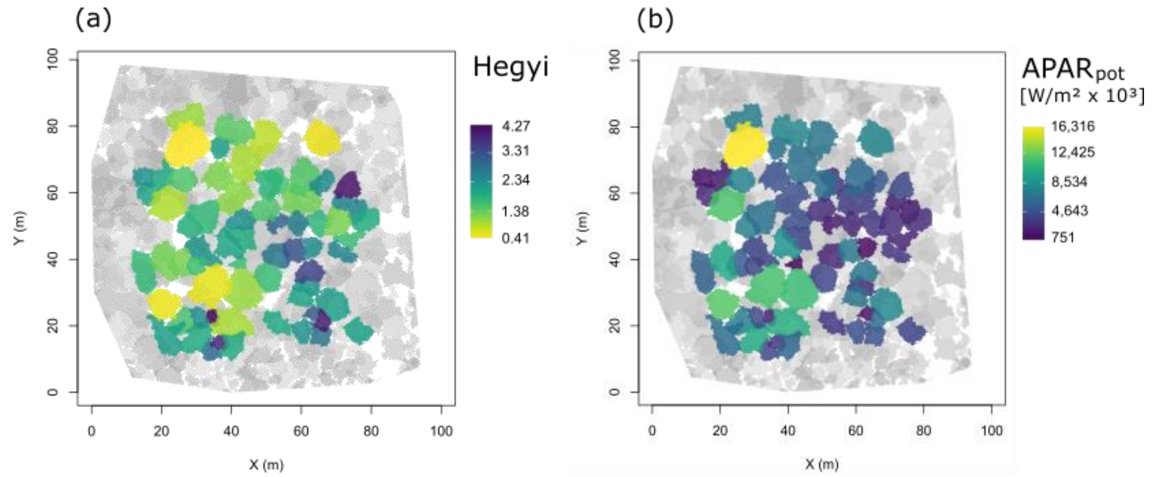

Figure 1 Crown projection areas of the trees in the Schönberg study site close to Freiburg. Coloured crown projection areas belong to the sample trees. (a) coloured by Hegyi's competition index. (b) coloured by estimated potentially absorbed photosynthetically active radiation ($APAR_{pot}$) in W/m^2 (x 10^3) summed up over the vegetation period.

Relevance and Future Directions

This study explores competition dynamics in European beech, introducing a novel approach that directly assesses competition for light, unlike traditional indices that summarize multiple competitive aspects. By integrating TLS and RTM, we capture complex tree structures and estimate light availability shaped by shading and spatial arrangement. By avoiding assumptions about tree-to-tree interactions, this method provides a more accurate understanding of how light availability influences growth.

This research offers valuable insights for both scientists and forest managers, providing refined methods for quantifying competition dynamics and advancing tree growth and forest ecology research. Forest growth modelling will benefit from a better understanding of competition, leading to more accurate predictions of forest productivity and carbon sequestration under varying environmental conditions. These findings can help forest managers optimize composition and management strategies to enhance tree growth potential and forest ecosystem resilience.

This study represents a key step in addressing competition for light. Further research is needed on other competition aspects, including water and nutrient limitations. Future studies could also examine competition dynamics at smaller temporal scales, integrating measurements of water availability to better understand tree stress periods. Collaboration with forest managers, modelers, and ecologists will be vital for refining methods and advancing both theoretical and practical applications in forestry.

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