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Assessing stand structure of beech and spruce from measured spectral radiation properties and modeled leaf biomass parameters

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ABSTRACT

Solar radiation is crucial for growth and competition within forest ecosystems. The spectral waveband between 400 and 700 nm is mainly responsible for photosynthesis and thus for plant growth. Within this spectral waveband, single spectral ratios (e.g. blue/red, green/red, red/far-red) influence and trigger different processes like leaf expansion, germination, stem growth and flowering. Spectral irradiance and biomass are heavily interrelated. Spectral radiation measurements covering the range 360–1020 nm were carried out with 130 sensors in six stand levels in a mixed plantation of Norway spruce (*Picea abies* [L.] Karst) and European beech (*Fagus sylvatica* L.). However, direct measurements of vertical and horizontal distributions of foliage are very complex and time-consuming and for this reason foliage biomass parameters of leaf area index (LAI) and specific leaf area (SLA) modeled by the growth model BALANCE are useful parameters to give complete stand representations. The interaction between modeled biomass parameters of European beech and Norway spruce and measured radiation profiles through all stand levels in this unique spectral and spatiotemporal resolution was the aim of this study. Both species showed the typical response to variation in light availability for both modeled parameters. Results exhibit a significant negative relationship between LAI and the photosynthetical photon fluence rate (PPFR) for both species. The blue/red (B/R) ratio showed significant negative relationships to LAI of both species. The vertical distribution of green/red and red/far-red in respect to LAI varied depending on the species and their morphological crown habit. Analyses of SLA and radiation under spruce showed no significant relationship at all. In contrast, beech showed significant relationships of SLA and the spectral ratios of red/far-red and blue/red.

1. Introduction

Among various foliage biomass factors, light quality and quantity play important roles within forest ecosystems. Spectral irradiance within forest stands is strongly influenced by the architecture and distribution of foliage biomass in the canopy. The reverse is also true; with radiation influencing production of foliage biomass. This interdependence underpins the complexity of merging leaf biomass parameters and radiation datasets to understand their interactions better. Various studies (e.g. Hertel et al., 2011; Leuchner et al., 2007; Navrátil et al., 2007; Serrano and Peñuelas, 2005) have shown that highly resolved spectral measurements are a tool to assess the complex canopy structure. The assessment of the distribution of the whole-tree foliage biomass is an important prerequisite to analyze its interaction with light. However, direct measurements of vertical and horizontal distributions of foliage are very complex and time-consuming in mature forest stands. Another crucial point is that optical foliage biomass measurements (e.g. Li-Cor LAI 2000, hemispherical fisheye photographs) deliver only useable results from ground level, with uncertainties at other levels. For this reason forest growth models can be a useful alternative to direct leaf collection and optical measurements. Furthermore modeled parameters and radiation measurements with optical fibers in different stand heights (Leuchner et al., 2005) are non-destructive and are able to capture long and consistent time series.

One of the key parameters used to describe canopy structure and give stand representations is the leaf area index (*LAI*). The *LAI* ($m^2\ m^{-2}$) quantifies the total amount of leaves or needles within a canopy and is defined as the total one-sided area of leaves per unit of ground surface area (Pokorny et al., 2008; Watson, 1947). The *LAI* represents the foliage which intercepts photons, transfers energy, and exchanges carbon and water vapor between forest stands and the atmosphere (Pokorny et al., 2008). Various studies (Reiter, 2004; Wang et al., 2004; Pretzsch et al., 1998) report mean *LAI* values for beech ranging between 4 and 6 during the period of

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full foliation and for spruce between 4 and 8. Higher *LAI* values are not necessarily related to greater biomass production. Seasonal *LAI* changes in deciduous forests are experienced during leaf unfolding and senescence. Chen (1996) also investigated seasonal variations in *LAI* in coniferous forest stands of about 25–30% during growth cycles.

Another focus is on the determination of the specific leaf area (*SLA*) that is strictly linked to that of *LAI*. *SLA* ($m^2\,kg^{-1}$) is a measure of leaf thickness and is defined as projected leaf area per unit leaf dry mass and relates to light conditions in deciduous and coniferous tree species. *SLA* is therefore well suited to characterize the physiological and morphological properties of the foliage within branches, which experiences gradually changing light conditions. Light, and therefore *SLA*, scales with height in the canopy (Landhäuser and Lieffers, 2001; Kazda et al., 2000; Niinemets et al., 1999; Cemark, 1998; Morales et al., 1996; Matyssek, 1986). Cemark (1998) reported a strong increasing vertical *SLA* gradient for beech stands which was related to the cumulative *LAI* profile through the canopies. Thus, *SLA* at a particular crown location is directly or indirectly related to light availability at that point. The morphological adaptation of leaves leads to the determination and differentiation of sun and shade leaves (e.g. Reiter, 2004; Abrams and Mostoller, 1995). Sun adapted foliage shows a significantly higher photosynthetic activity compared to shade adapted foliage (Urban et al., 2007; Marek et al., 1999).

While recent work has described the role of canopy structure on light transmittance in various forest stands (Leuchner et al., 2007; Pecot et al., 2005) information is lacking how different spectral properties vary in different stand layers and how they are statistically related to biomass parameters such as described above. Different radiation properties between direct and diffuse radiation at different canopy heights influence morphological processes. Overcast sky conditions (OVC) have a major effect on the spectral irradiance within canopies. Various spectral wavebands and ratios such as the red/far-red ratio (R: 655–665 nm, FR: 725–735 nm) exhibit specific behavior under OVC conditions. Studies have shown that R/FR decreases under OVC conditions and below denser canopies (Hertel et al., 2011; Leuchner et al., 2007; Pecot et al., 2005; Endler, 1993; Holmes and Smith, 1977). Below deciduous trees, R/FR declines more than under coniferous canopies triggered by a higher selective transmission of light and a higher absorption of R light by the leaves (Leuchner et al., 2007; Lieffers et al., 1999; Federer and Tanner, 1966). Furthermore, plants can use diffuse sky conditions more effectively than direct radiation for photosynthetic activities (Campbell and Norman, 1998). As solar radiation penetrates into the canopy, the spectral composition changes due to absorption, reflection and transmission e.g. for the blue/red ratio (B_W: broadband blue 400–500 nm; R_W: broadband red 600–700 nm) as shown by Hertel et al. (2011) and Navrátil et al. (2007). This increase of B_W/R_W may stimulate photosynthetic activity (Matsuda et al., 2007; Vogelmann and Martin, 1993). There is little knowledge about the green/red ratio (G_W: broadband green 500–600 nm, R_W: broadband red 600–700 nm). The green waveband usually has relatively higher reflectance. Grant (1997) and Navrátil et al. (2007) observed the highest relative proportion of G_W photons under clear sky (CS) conditions and at solar noon. All the ratios described above are within the photosynthetically active radiation (PAR: 400–700 nm) waveband. PAR is absorbed by chlorophyll in the PSI and PSII photosystem and carotenoids (Grant, 1997).

In order to address the objectives to estimate structural stand attributes in complex forest stands a combination of models and measurements were used with the help of spatially and temporally highly resolved data for mature forest stands. The importance and usefulness of spectral measurements were evaluated above.

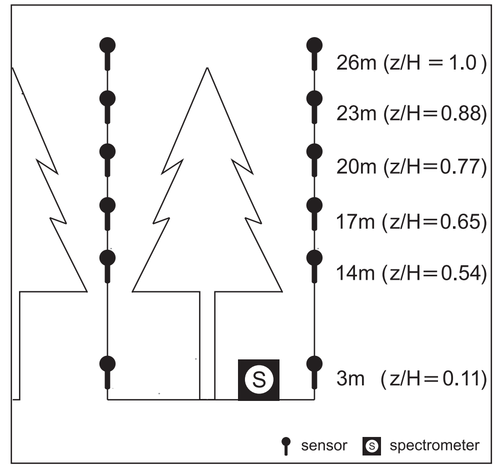

Fig. 1. Scheme of the experimental setup of sensor profiles within the forest stand.

In addition the overall objectives of the current study were (1) the description of stand structure by measured vertical radiation profiles from the period of full foliation until after defoliation to track seasonal changes for the implementation in further studies and (2) the comparison of a measured spectral radiation dataset with modeled leaf biomass parameters to detect detailed relationships between these factors.

2. Materials and methods

2.1. Radiation data

The intensive investigation plot 'Kranzberger Forst', 35 km NE of Munich, Germany (48°25′08″N, 11°39′41″E, 485 m a.s.l.), where all radiation measurements were obtained is a mixed plantation of Norway spruce (*Picea abies* [L.] Karst) and European beech (*Fagus sylvatica* L.). In 2005 the spruce stand was 54 years old and the beech stand 61 years old with a single storey structure. For the main research area a number of 194 trees and a single story structure were given with a total area of 30 m × 30 m. The shortest distance between a sensor profile and a small clearing was about 15 m, thus avoiding significant influence of clearings on the data (Hertel et al., 2011). The maximum leaf area density for beech was situated in the upper third and for spruce in the lower half of the canopy (Häberle et al., 2003). The basal area is 46.4 m^2/ha the stand density 764 stems/ha (Wipfler et al., 2005). The measurements were performed by a self-built 130 sensor system consisting of a miniature multichannel spectrometer (Zeiss MCS module UV–VIS–NIR) with quartz glass optical fibers (0.6 mm core diameter) and sensor heads of white 10 mm polyoxymethylene spheres (Leuchner et al., 2005). The system was developed with a total measuring cycle of 2 min 15 s for all 130 locations providing a quasi-simultaneous acquisition of the entire three-dimensional radiation regime in the stand. The spectral range obtained was 360–1020 nm with a high spectral resolution of 0.8 nm. An extensive description of the single components and the calibration procedure is described by Leuchner et al. (2005). Spectral measurements were performed on a regular grid consisting of 25 vertical profiles in five different stand layers (3 m: $z/H = 0.11$, 14 m: $z/H = 0.54$, 17 m: $z/H = 0.65$, 20 m: $z/H = 0.77$ and 23 m: $z/H = 0.88$; z/H represents the relative height to the apex) and above the canopy (26 m: $z/H = 1.0$) (Fig. 1). From this experimental setup, it was possible to produce a very detailed description of the spatial distribution of solar radiation for both beech and spruce. In order to address the objectives of this study, analyses were performed for beech and spruce for all weather conditions during the different phenological stages of full foliation (August,