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Estimation of the seasonal leaf area index in an alluvial forest using high-resolution satellite-based vegetation indices

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ABSTRACT

The leaf area index (LAI), as a key indicator of physical and biological processes related to vegetation dynamics, is valuable in monitoring the biomass of forests. Based on the phenological development of trees, the LAI shows high seasonal variability. This study estimated the LAI through field measurements and satellite-derived spectral vegetation indices (SVIs) in two alluvial forest sites at species level (black alder). The primary objective of this study was the validation of seasonal relationships between field-measured LAI, using a LI-COR 2200 plant canopy analyzer (PCA), and four red edge and non-red edge satellite-derived spectral vegetation indices (SVIs) of 10 high spatial resolution RapidEye images: the normalized difference vegetation index (NDVI), the red edge NDVI (NDVI-RE), the modified red edge simple ratio (mSR-RE), and the curvature. The indices were compared using 4 phenological phases (leaf flushing until crown closure, leaf growth under crown closure, decreasing leaf chlorophyll content, and leaf senescence) over the entire vegetation period in 2011 using regression analyses, *t*-test and root mean square error (RMSE). The results suggest that the LAI–SVI relationships varied seasonally. Strong to weak linear relationships were obtained during different periods. For each phase, a different SVI fitted best: NDVI-RE during leaf flushing until crown closure ($R^2 = 0.62$, RMSE = 0.47), mSR-RE during leaf growth under crown closure ($R^2 = 0.422$, RMSE = 0.71), NDVI-RE during decreasing leaf chlorophyll content ($R^2 = 0.182$, RMSE = 0.58), and NDVI during leaf senescence ($R^2 = 0.829$, RMSE = 0.53). Thus, implementing the red edge channel improved the LAI–SVI relationships, particularly during periods with few variations in the LAI. An analysis of the entire vegetation period revealed that NDVI had the best regression ($R^2 = 0.942$, RMSE = 0.507) because it was the most stable index due to moderate LAI values (average max. LAI = 4.63). The satellite-based vegetation indices used in this study provided reliable estimates and described the temporal changes and spatial variability in the LAI well. It can be concluded that a LAI–SVI relation cannot be established by a single linear regression throughout a year. Hence, a multi-temporal approach is recommended when monitoring alluvial forest dynamics. Future research on estimating the LAI based on satellite imagery should include the phenological phases into the calculation.

1. Introduction

The regular and accurate observation of forest status and damages caused by nitrogen deficiencies, water stress or insect diseases can facilitate the development of adequate management strategies. Particularly in terms of climate change, the effect of forest stress and phenological timing shifts might be intensified (Ahl et al., 2006; Liang, Schwartz, & Fei, 2011; Myneni, Keeling, Tucker, Asrar, & Nemani, 1997; White, Thornton, & Running, 1997).

One key feature for monitoring forest ecosystems is the canopy structure, which influences and is influenced by the processes of the ecosystem, such as temperature, moisture or net primary productivity, and changes within minutes, seasons, and years (Weiss, Baret, Smith, Jonckheere, & Coppin, 2004). An important characteristic of the canopy structure is the leaf area index (LAI) (Chason, Baldocchi, & Huston, 1991). This index is a key indicator for the analysis of physical and biological processes related to the vegetation dynamics at global and regional scales, such as energy exchange, water, and carbon cycle (Chen et al., 2002; Fassnacht, Gower, & Norman, 1994). Watson (1947) first defined the LAI as a dimensionless quantity, the total one-sided area of photosynthetic tissue per unit soil surface area. The LAI is a quantity for the potential area of a habitat, which is photosynthetically active. For temperate deciduous forests, the phenology determines the length of the growing season. Therefore, the seasonal course of a biome's LAI can be used to describe its intra-annual phenology (Wang, Tenhunen, et al., 2005).

The LAI can be derived through direct measurements and indirect estimates (Asner, Scurlock, & Hicke, 2003; Jonckheere et al., 2004).

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Direct methods involve the destructive sampling of leaves, litterfall collection, or point contact sampling (e.g., Chason et al., 1991; Wang, Adiku, et al., 2005). For indirect measurements, optical instruments, models, and remote sensing data are used (e.g., Bréda, 2003; Dufrêne & Bréda, 1995; Wang, Adiku, et al., 2005). Direct estimates provide the closest values to the true LAI, but they are time-consuming, labor-intensive, and destructive, which is undesirable, particularly in protected forests (Eschenbach & Kappen, 1996; Fassnacht et al., 1994). Thus, there is great interest in using remote sensing data to estimate the LAI. This method is particularly suitable for monitoring vegetation, allowing the collection of a larger spatial and temporal sample with minimum effort (Jonckheere, Muys, & Coppin, 2005).

Since the 1970s, the LAI has been known to be strongly related to spectral measurements because it is directly linked to reflectance characteristics of vegetation (Chen, Vierling, Deering, & Conley, 2005; Tucker, 1979). Thus, many studies with different biomes including croplands, plantations and forests (conifer and deciduous stands) have successfully linked LAI measurements on the ground, using either direct or indirect techniques, to remote sensing data (e.g., Brantley, Zinnert, & Young, 2011; Chen & Black, 1991; Chen & Cihlar, 1996; Colombo, Bellingeri, Fasolini, & Marino, 2003). Chen and Cihlar (1996), Turner, Cohen, Kennedy, Fassnacht, and Briggs (1999), and Chen et al. (2005), for example, used a priori functions to upscale LAI measurements from plot level to regional scale using remotely sensed data. These studies correlated spectral vegetation indices (SVIs), like normalized difference vegetation index (NDVI), simple ratio (SR), and/or soil-adjusted vegetation index (SAVI) from different satellite data (e.g., Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper Plus (ETM+), Moderate Resolution Imaging Spectroradiometer (MODIS)), to ground-based measurements. The type of relationship between LAI and different combinations of SVIs was analyzed in a variety of studies. Besides linear, quadratic polynomial, and cubic polynomial links, most studies have shown logarithmic relationships (Chen & Cihlar, 1996; Datt, 1999; Le Maire et al., 2011; Mutanga & Skidmore, 2004; Myneni, Hall, Sellers, & Marshak, 1995; Potithep, Nagai, Nasahara, Muraoka, & Suzuki, 2013; Tucker, 1979; Turner et al., 1999).

Characteristics of green leaves are exploited for the generation of SVI. Although they are species dependent, these characteristics show similar features. In visible light (0.4–0.7 μm), the reflection is low because maximum chlorophyll absorption is observed, particularly at 0.69 μm (red wavelength). In the near-infrared region (NIR, 0.7–1.3 μm), leaves reflect solar radiation as a consequence of their internal mesophyll cellular structure and leaf surface scattering. If leave-chlorophyll-content is high, this results in a high reflection, and therefore in a high SVI and LAI (Chen et al., 2005; Myneni et al., 1995). Many SVIs were suggested to reduce unwanted environmental noise in satellite data caused for example by solar geometry, uneven atmospheric conditions, topography, and secondary canopy effects (Chen et al., 2005; Hwang, Song, Bolstad, & Band, 2011; Lillesand, Kiefer, & Chipman, 2008). Thus, SVI measurements enhance the responsivity to canopy characteristics, such as LAI (Chen et al., 2005; Wu, Wang, & Bauer, 2007). Most spectral vegetation indices combine red/near-infrared bands to utilize leaf attributes (Reed, White, & Brown, 2003). These indices are useful for forest monitoring because damages affect the absorption of photosynthetically active radiation induced through the loss of chlorophyll (Eitel et al., 2011).

A variety of studies used satellite systems with low to moderate spatial resolution (e.g., NOAA Advanced Very High Resolution Radiometer (AVHRR) (1.1 km), Système Pour l'Observation de la Terre Vegetation (SPOT-4) (1 km), Terra MODIS (250 to 1000 m), Landsat-5 TM (30 m), Landsat-7 ETM+ (15–60 m)), to relate the ground-based LAI to remote sensing data (e.g., Chen et al., 2002, 2005; Wang, Adiku, et al., 2005). However, because of the heterogeneity of the earth's surface, data with a low to medium spatial resolution contain mixed pixels and subsequently supply most likely a LAI information of different vegetation types (Chen et al., 2002; Eitel, Long, Gessler, & Smith, 2007). Previous studies utilized frequently Landsat and SPOT-4 imagery because of their large temporal and spatial scale (e.g., Berterretche et al., 2005; Fassnacht, Gower, MacKenzie, Nordheim, & Lillesand, 1997; Kobayashi, Suzuki, & Kobayashi, 2007; Wang, Adiku, et al., 2005). These data are cost effective and cover large areas, but they lack spatial resolution. Hence it is challenging to differentiate tree species in small and diverse landscape units. Especially within a Terra MODIS pixel size of up to 1000 m, it is highly likely that multiple tree types would be mixed in a single pixel. For this reason, the SVIs have been estimated using high-spatial resolution satellite data in recent studies. IKONOS with a spatial resolution of 4 m, QuickBird with a spatial resolution of 2.8 m, and RapidEye data with a spatial resolution of 5 m were used to estimate the LAI of different agricultural crops and grasslands (Chen, Vierling, Rowell, & DeFelice, 2004; Colombo et al., 2003; Wu et al., 2007).

LAI estimations depend on species composition, development stage, stand conditions, seasonality, and the management practices used (Jonckheere et al., 2004). The changing phenology and environmental conditions affects the seasonal LAI course during various development stages of mid-latitude vegetation. The multi-temporal analysis of surface reflectance is necessary to examine changes in the vegetation surface. Even though this is an important aspect, it has been neglected in most mono-temporal studies, although it is crucial for the transfer of the outcomes to other acquisition dates. Most studies have estimated the LAI using data from only one developmental stage (mostly June to August) (e.g., Chen, 1996; Chen et al., 2002; Colombo et al., 2003). First results in multi-temporal remote sensing-based estimation of the LAI under different phenological stages can be found in Kodani, Awaya, Tanaka, and Matsumura (2002), Wang, Adiku, et al. (2005), Eitel et al. (2011), Heiskanen et al. (2012) and Potithep et al. (2013). However, these results were based on low spatial resolution data (e.g., AVHRR, MODIS) or non-forest application fields (e.g., wheat nitrogen).

In the presented study, the important and innovative aspect of the relation of field-based and satellite-based seasonal LAI dynamics of black alder (*Alnus glutinosa*) was investigated. The LAI field measurements were related to a time-series of ten satellite images from a single vegetation period using four red edge and non-red edge spectral vegetation indices: the normalized difference vegetation index (NDVI) (Rouse, Haas, Schell, & Deering, 1973; Tucker, 1979), the red edge NDVI (NDVI-RE) (Gitelson & Merzlyak, 1994; Sims & Gamon, 2002), the modified red edge simple ratio (mSR-RE) (Datt, 1999; Sims & Gamon, 2002), and the curvature (Conrad et al., 2012). These indices were additionally used to estimate the advantages of red edge vs. non-red edge. As development of satellite sensors heads toward the introduction of additional bands, RapidEye products were used as high-resolution satellite images including the red edge spectrum. In situ LAI-time series obtained using an optical LI-COR 2200 plant canopy analyzer (LI-COR) served as reference data.

The novelty of this study is the estimation of the LAI over an entire vegetation period (April to November) at a high spatial resolution, sufficient for a species-related information in an alluvial forest. Since the LAI includes the biomass in the tree layer below the top canopy, the assumption of this study is, that the intra-annual temporal development of the LAI is differing for field-based and satellite-based measurements, due to further leaf foliage in lower tree layers while the top canopy is fully developed. Therefore, future research would have to adapt the derived LAI based on the phenological stage of the year. In addition, the study is utilizing combined high spatial and temporal resolution satellite data. Due to repeated ground-based and satellite-based measurements multi-temporal estimations of SVIs in black alder stands under different phenological stages are possible.

The main aims of this study are:

- A comparison of ground-measured LAI and four red edge and non-red edge satellite-derived spectral vegetation indices of alluvial forests, and
- The exposure of possible advantages of multi-date LAI analysis over the entire vegetation period compared with the LAI values obtained from a single phenological phase.