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Specific leaf area estimation from leaf and canopy reflectance through optimization and validation of vegetation indices

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ABSTRACT

Specific leaf area (SLA), which is defined as the leaf area per unit of dry leaf mass is an important component when assessing functional diversity and plays a key role in ecosystem modeling, linking plant carbon and water cycles as well as quantifying plant physiological processes. However, studies of SLA variation across relevant spatial and temporal scales are lacking. While remote sensing is a fast and efficient approach to quantify vegetation parameters, there are insufficient studies estimating SLA from remotely sensed data. This article aims at finding efficient hyperspectral indices for fast and accurate estimation of SLA from leaf and canopy spectral measurements. Validation of our results with data measured at leaf and canopy scale as well as with experimental datasets simulated using PROSPECT (at leaf level) and INFORM (at canopy level) revealed SLA was predicted accurately by several indices, such as simple ratio and normalized index types. Most of the bands sensitive to SLA selected using these indices were in the 1300–1800 nm spectral region. At leaf level, a ratio index at bands1370 nm, 1615 nm performed strongly (R^2 = 0.93 and RMSE = 13.66 cm^2/g) during cross-validation. The multiband indices with 920 nm, 1675 nm, 1335 nm and 1345 nm, 1675 nm, 1850 nm central wavelengths were also among the top performing indices, with R^2 > 0.90 for both measured and simulated leaf level data. At canopy level, the soil adjusted ratio vegetation index (with a band setting of 1537 nm, 1543 nm) showed that the hyperspectral data from HySpex airborne imagery accurately estimated SLA (R^2 = 0.88 and RMSE = 13.30 cm^2/g). Generally at canopy level the potential indices for accurate retrieval of SLA from HySpex imagery were two-band indices with soil line information. The discrepancy observed in the performance and band combinations of vegetation indices at leaf and canopy scales can be explained by external factors such as canopy structure, soil background, illumination and sensor configuration which affect the signal when moving from leaf to canopy level. Our findings suggest the availability and suitability of a wide range of existing vegetation indices for assessing SLA accurately and rapidly from remotely sensed data.

1. Introduction

Specific leaf area (SLA) is one of the fundamental leaf functional traits attributed to the functional component of biodiversity (Wilson et al., 1999; Asner et al., 2011) and is among the ten essential biodiversity variables proposed by Skidmore et al. (2015) to capture biodiversity change from space. SLA is defined as the leaf area per unit of dry leaf mass, usually expressed in m^2/kg. It is also commonly referred to as leaf mass per unit area, specific leaf mass, or leaf specific mass. It links plant carbon and water cycles (Pierce et al., 1994), and in many large-scale ecosystem models, canopy-average SLA is recognized as an important ecosystem variable. Since SLA regulates plant physiological processes such as light capture, growth rates, and life strategies, it provides information on the spatial variation of photosynthetic capacity and leaf nitrogen content (Pierce et al., 1994). A worldwide foliar dataset indicated that 82% of all variation in photosynthetic capacity can be explained by variation in SLA and nitrogen content (Wright et al., 2004). SLA is species-specific, but significant plasticity exists within and between individual plants of the same species (Pierce et al., 1994; Asner et al., 2011). Usually, high SLA occurs in areas with high water and nutrient availability (Long et al., 2011). Plants growing at high

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altitude generally have a lower SLA than plants of the same species in lower elevations (Wilson et al., 1999).

Although remote sensing – in particular, hyperspectral imagery – has emerged as a powerful platform for measuring or estimating biochemical and biophysical vegetation parameters, few operational methods have been developed for quantifying SLA at landscape, regional or global scales from remote sensing data. Therefore, developing robust and operational algorithms that can accurately predict plant functional traits (e.g., SLA) from remotely sensed data at different scales is pivotal.

Two types of approach have been developed to estimate vegetation parameters from remote sensing data or reflectance measurements: (i) empirical (such as indices and/or multiple regressions), and (ii) radiative transfer models (RTM) inversion. The most commonly used method in the empirical approach is the vegetation index (VI). Vegetation indices (VIs) constitute simple and convenient algebraic combinations of spectral reflectance to extract information from remotely sensed data, which facilitates the processing and analysis of large amounts of remotely sensed data. In other words, reflectance measurements at various spectral bands are mathematically combined to empirically correlate reflectance (or reflectance indices) to a particular vegetation parameter such as SLA. These approaches are simple and fast to apply, but have the limitation of often being site-specific because the representativeness of the relationship is limited to the representativeness of the database (le Maire et al., 2008). In addition, the effectiveness of a VI is limited to different degrees by the effect of perturbing factors such as atmospheric conditions, topography, illumination and viewing geometry, sensor calibration, soil background, and canopy vertical heterogeneity, vegetative growth stage or conditions (e.g., Mottus et al., 2012; Sun et al., 2012; Wang and Li, 2013; He et al., 2014; Qi et al., 2014; Zhu et al., 2014; Savoy and Mackay, 2015).

On the other hand, RTMs allow the creation of simulated training databases covering a wide range of spectral data to which inversion algorithms such as Look-Up Tables inversion and Artificial Neural Network can be applied to retrieve parameters from remote sensing data. Inversion of such models often yields a large number of different possible solutions for a specific variable. Furthermore, uncertainties in measurements and models may result in large variation in results (Combal et al., 2003). It is also difficult to obtain optimal parameterized solutions for radiative transfer model inversions (Atzberger et al., 2011), which can also lead to challenges when extrapolating models in space and time. Besides, the RTM approach is computationally demanding and requires a large number of leaf and canopy model input parameters.

Despite having limitations, because of their ease of computation and capacity, VIs have been used to enhance the information contained in spectral reflectance data. In the past four decades, a number of researchers (e.g., Rouse et al., 1974; Clevers, 1991; Gitelson, 2004; Quiring and Ganesh, 2010; Ullah et al., 2013; Wu 2014) have sought to develop spectral vegetation indices at various scales ranging from leaf to global, in order to monitor the Earth's vegetation cover and retrieve vegetation parameters such as leaf chlorophyll, leaf area index (LAI), fractional vegetation cover, biomass, canopy architecture, and photosynthetic activity from remotely sensed data. Many ecosystem researchers (e.g., Wu et al., 2008; Peng and Gitelson, 2011; Gonsamo et al., 2012; Sun et al., 2012; Wu, 2014; Zhang et al., 2015) have widely applied VIs and hyperspectral narrow bands to remote sensing data for land cover classification, biomass and net primary production (NPP) quantification, crop yield estimation, land degradation monitoring, soil mapping, and vegetation–climate interaction assessment.

Various VIs have been proposed to minimize the effects of perturbing factors and maximize accurate retrieval of vegetation parameters. For instance, soil-adjusted VIs (e.g., Huete, 1988; Ren and Zhou, 2014) to correct for the perturbation of soil background based on the soil line information, and atmospherically resistant VIs (e.g., Gitelson et al., 2002) to minimize atmospheric noise or to reduce both soil influence and atmospheric effects or environmental conditions (e.g., Liu and Huete, 1995; Huete et al., 1997; Petros et al., 2011).

Among vegetation parameters retrieved using hyperspectral data, SLA has received little attention. Few ratio-based indices have been tested for retrieval of SLA mainly by means of simulated data, either at leaf level (le Maire et al., 2008; Romero et al., 2012) or at canopy level (le Maire et al., 2008). Optimization of VIs using simulated data, however, has failed to address the uncertainty and discrepancies between measured and simulated spectral datasets. In addition, the suitability of many of the indices available in the literature (other than the ratio type) are not yet been evaluated for SLA retrieval. Here we optimized and validated the suitability of a number of vegetation indices previously proposed for retrieving various vegetation properties (see Table 4) for remotely estimating the SLA from leaf and canopy reflectance for heterogeneous mountain forest with contrasting leaf structures and canopy architectures.

2. Methods

2.1. Study site

The study site was the mixed mountain forest of the Bavarian Forest National Park, which is located in south-eastern Germany along the border with the Czech Republic (49° 3′ 19″ N, 13° 12′ 9″ E). Elevation of the study site varies from 600 m to 1473 m above sea level. The climate of the region is temperate, with high annual precipitation (1200 mm to 1800 mm) and low average annual temperature (3–6 °C). Heavy snow cover is characteristic of the area in winter. Brown soils which consist mostly of fresh, primarily sandy, deep weathered loam with, as a rule, a small portion of skeletal soil are the predominant soil type at lower altitude (below 900 m asl) whereas at high altitude (above 900 m asl) loose brown soils and brown podzolic soils which are characterized by a large looseness of the soil fabric owing to a high total soil porosity and a high humus content predominate. The soils in the area are naturally acidic and low in nutrient content. The natural forest ecosystems of the Bavarian Forest National Park vary with altitude: above 1100 m there are sub-alpine spruce forests with Norway spruce and some mountain ash (*Sorbus aucuparia* L.); on the slopes, between 600 and 1100 m altitude, are mixed montane forests with Norway spruce, white fir (*Abies alba* MILL.), European beech and sycamore maple (*Acer pseudoplatanus* L.); in wet depressions, often associated with cold air pockets in the valley bottoms, spruce forests with Norway spruce, mountain ash and birches (*Betula pendula* ROTH., *Betula pubescens* EHRH.) occur there are alluvial spruce forests in the valleys, mixed mountain forests on the hillsides and mountain spruce forests in the high areas. The dominant tree species include European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*) and Fir (*Abies alba*). In the mixed mountain forests Sycamore maple (*Acer pseudoplatanus* L.), Mountain ash (*Sorbus aucuparia* L.) and Goat willow (*Salix caprea*) are also found. Due to heavy disturbance by bark beetles and wind storms in recent decades the forest structure in the park is very heterogeneous (Lehnert et al., 2013).

2.2. Analytical frame work

The procedure followed during optimization and validation of indices is illustrated in Fig. 1. Using the measured datasets, for each VI, the highest correlation between SLA and combination of spectral bands was identified for leaf and canopy reflectance. At leaf