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Estimating leaf chlorophyll status using hyperspectral lidar measurements by PROSPECT model inversion

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ABSTRACT

Chlorophyll (Chl) is an important indicator of photosynthetic capacity and stress of vegetation. Remote sensing provides fast and nondestructive methods for estimating leaf Chl content based on its optical characteristics in visible and near-infrared spectrum. Multispectral lidar (MSL) systems have been developed to combine spectral and spatial detection abilities. Statistical relationships of plant biochemical constituents can be established through MSL measurements. However, empirical models cannot be readily extended to independent datasets. Simultaneously, the few spectral bands of MSL limit the use of a physical model. Hence, the development of hyperspectral lidar (HSL) systems offers a wider range of spectrum. This study investigated the possibility of adopting an HSL system with 32 channels covering 539–910 nm to estimate foliar Chl through a physical model. This study aimed to (1) Determine whether reflectance at the 32 channels is sufficient to retrieve Chl content through PROSPECT model inversion and (2) Considering the difference between passively and actively measured reflectance, investigate whether HSL measurements can be applied into PROSPECT model inversion for leaf biochemical constituents. Three kinds of datasets were used: a synthetic dataset simulated by running the PROSPECT model in forward mode, a public dataset ANGERS taking the channels of the HSL system, and an experimental dataset of paddy rice measured by the HSL system. Results showed HSL measurements can be directly used to retrieve leaf Chl content through PROSPECT-4 model inversion (R^2 = 0.55). These measurements also exhibit higher accuracy than that of support vector regression (threefold cross validation; 100 repetitions: median R^2 = 0.47). This validation work provides basis in the determination of vegetation physiological status directly from HSL measurements through model inversion with the PROSPECT model.

1. Introduction

Photosynthesis is one of the most important processes that provides energy in ecosystems. The balance of photosynthesis and respiration is decisive for understanding the growth of individual plants and the carbon cycle of ecosystems (Springer, 2012). Furthermore, the uncertainty in vegetation ecosystem carbon cycle attracts considerable interest to assess the carbon sequestration on earth (Schlemmer et al., 2013). Chlorophyll (Chl), as an important indicator of photosynthetic capacity and vegetation stress, interacts with solar radiation and changes in response to environmental conditions (Féret et al., 2017).

Plant Chl content has been found to be closely related to gross primary production, which strongly influences food and biomass production globally (Peng et al., 2015). There is a close relationship between leaf Chl and nitrogen, and Chl content has long been used as an indirect method to quantify leaf N content and guide fertilisation or estimate crop yields (Baret et al., 2007; Schlemmer et al., 2013; Sun et al., 2017).

By using the specific optical characteristics in the visible and near-infrared spectrum, remote sensing techniques have proven useful for estimating leaf Chl quickly and nondestructively (Sims and Gamon, 2002; Ustin et al., 2009). Traditionally, multispectral images are widely utilised to link leaf spectral reflectance to physiological status (Clevers and Gitelson, 2013; Yoder and Pettigrew-Crosby, 1995). However,

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passive remote sensing systems typically rely on solar illumination, and they cannot easily provide the geometry information. On this basis, multispectral lidar (MSL) systems were proposed to combine the spectral and spatial detection capabilities (Chen et al., 2010; Gong et al., 2015; Wei et al., 2012). MSL measurements are applied in detecting leaf N concentration (Eitel et al., 2014), water condition (Gaulton et al., 2013), and Chl content (Hakala et al., 2015; Nevalainen et al., 2014), etc. based on empirical relationships, such as vegetation indices and machine learning algorithms. Nevertheless, the robustness of these empirical methods is limited by the representativeness of the training dataset and the specific measurement configuration. Yet the spectral information provided by MSL is not sufficient for physical model inversion.

With the development of hyperspectral lidar (HSL) systems, which utilize white supercontinuum laser as a light source and have dozens of detecting channels (Du et al., 2016), biochemical trait estimation based on radiative transfer models at leaf and canopy levels has become possible (Du et al., 2016). Leaf and canopy radiative transfer models describe the process of internal light reflection and transmission. They have clear physical significance and can be extended across species and circumstances. Among the leaf models, PROSPECT is one of the most popular. PROSEPCT-4 is developed based on the plate model (Allen et al., 1969), and it can simulate leaf reflectance and transmittance using leaf structure index (N), leaf Chl $a + b$ (C_{ab}), equivalent water thickness (EWT), and dry matter per area (LMA) (Feret et al., 2008).

To date, HSL spectral measurements have not been tested as input of the PROSPECT model, which was initially designed using passive reflectance. Consequently, two aspects are evaluated in the present study: (1) whether the 32 channels of the HSL system theoretically are sufficient to retrieve Chl content through PROSPECT model inversion and (2) whether actively acquired reflectance by the HSL system can be directly used to estimate Chl through PROSPECT model inversion.

2. Materials and methods

2.1. HSL system

The HSL system is a novel type of remote sensor that combines the spectral sensing ability of passive images and the spatial detecting ability of point cloud. Both spectral and geometry information can be acquired in one shot. Thus, the registration problem between datasets needs not be addressed. The HSL system adopted in this study is composed of four parts: laser source, receiving component, light-splitting component and light detection component. A supercontinuum laser source (NKT Photonics, SuperK) emits “white” light, which covers a wide range of wavelength (480–2200 nm). The target is illuminated, and the backscattered signals are collected by a Schmidt–Cassegrain telescope with a diameter of 0.2 m. To separate the polychromatic light into different wavelengths, a 150 g/mm grating with 500 nm blaze was used. A 32-element photomultiplier tube (PMT) arrays converted optical signals into analogue voltages (Du et al., 2016). The spectral response range of the system was 538–910 nm, and the spectral sampling interval of each element was 12 nm. Currently, the HSL system is still in the prototype development stage. There is no commercial HSL systems available.

2.2. PROSPECT model

PROSPECT is one of the first models to accurately simulate the directional-hemispherical reflectance and transmittance of plant leaves of different species over the whole optical domain (400–2500 nm) (Jacquemoud et al., 2009). Since the PROSPECT model was proposed in 1990 (Jacquemoud and Baret, 1990), several versions have been released by introducing new leaf biochemical constituents and improving the specific absorption coefficients for each biochemical parameter etc. (Fourty et al., 1996; Jacquemoud et al., 2000; Jacquemoud et al., 1996). The spectral resolution has been increased from 5 to 1 nm by Le Le Maire et al. (2004) in an unreleased version. The recent versions of PROSPECT-4 and 5 were released in 2008, improving the specific absorption coefficients for biochemical constituents and provided a new refractive index for the leaf interior (Feret et al., 2008). Their difference lies in the separation of carotenoids from total Chl. The latest version, PROSPECT-D, also included the calibrated specific absorption coefficient of anthocyanins (Féret et al., 2017).

Total Chl, water, and dry matter contents of a leaf were explicitly considered in the PROSPECT-4 model. Running the PROSPECT-4 model in the forward mode can calculate leaf reflectance and transmittance by assigning the values of leaf parameters: N, Chl, EWT, and LMA. Among them, the structure parameter N cannot be experimentally observed. It is the number of stacked elementary homogeneous layers of a leaf. In the inverse mode, leaf biochemical characteristics can be retrieved through the model by inputting the initial values, leaf reflectance, and transmittance. In this process, different values of leaf parameters are tried to simulate reflectance and transmittance. A merit function is used to compare the simulated reflectance and transmittance with the measured reflectance and/or transmittance. The parameter set that minimizes the merit function is finally provided as the retrieved values.

Sun et al.'s (2018) study found that using only reflectance or transmittance can retrieve some leaf biochemical constituents accurately. Traditional inversion methods use reflectance and transmittance of the whole optical range, while some studies suggested using a specific subset of spectral range to retrieve each parameter (Li and Wang, 2011).

2.3. Data description

To determine whether the 32 channels of the HSL system theoretically are sufficient to determine the Chl content through PROSPECT model inversion, two datasets were utilised: a synthetic dataset and public dataset ANGERS (Feret et al., 2008).

The synthetic dataset (n = 500) was simulated by running the PROSPECT-4 model in forward mode. For this, different combinations of leaf variables with different contents should first be generated. These combinations were achieved by assuming Gaussian distribution for each leaf variable, with parameters based on the study of Féret et al. (2011). Additive random Gaussian noise with standard deviation (std.) of 2% of the reflectance amplitude was applied on each wavelength of reflectance to avoid specific artefacts on simulations. This level of random noise was added based on previous studies (Féret et al., 2011; Li and Wang, 2011). Considering that each channel of the HSL system collects the backscattered signals in a spectral range rather than at a specific wavelength, the averaged reflectance in the corresponding channel was calculated to generate synthetic HSL measurement.

Given that the synthetic dataset only contains random error, the public dataset ANGERS leaf optical properties database was used. This dataset was measured by S. Jacquemoud etc. in June 2003, in the city of Angers, France. It incorporates measurements of 276 leaves corresponding to 43 different species, various growing conditions and growth stage. Leaf directional–hemispherical reflectance and transmittance spectra (400–2450 nm) were measured in 1 nm resolution with spectrophotometers equipped with integrating spheres. After the spectral measurements, leaf discs were sampled for biochemicals. Chl a, Chl b, total carotenoid content, EWT, and LMA were measured. The methods to extract and determine the biochemical contents were described in Feret et al.'s (2008) study. Similar to the synthetic dataset, reflectance in ANGERS was recalculated for application into the detection mechanism of the HSL system to represent the HSL measurement towards a variety of woody and herbaceous species, with varying leaf internal structures and biochemical compositions.

The HSL system collects the backscattered intensity of targets, with a small field of view (FOV, less than 3 mrad). In an active lidar measurement, only a small spot on the target is illuminated and observed