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Wavelet-based coupling of leaf and canopy reflectance spectra to improve the estimation accuracy of foliar nitrogen concentration

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ABSTRACT

The leaf or canopy reflectance spectra of vegetation have been widely employed in estimating foliar nitrogen (N) concentration; however, they alone may not actually reflect the spectral and detailed information at a sampling plot. In this study, the potential spectral details of *Carex* (*C. cinerascens*) at a plot scale were derived using discrete wavelet transform, in which a simple operation of addition was employed to combine the reconstructed leaf and canopy reflectance at the fourth decomposition level (named "leaf-canopy d4 reflectance"). Partial least squares regression (PLSR), successive projections algorithm-based multiple linear regression (SPA-MLR) and random forest regression (RFR) models with leaf, canopy and leaf-canopy d4 reflectance were established and validated for foliar N estimation, respectively. The results showed that the PLSR (R^2_{CV} = 0.718, determination coefficient of cross-validation; R^2_{Val} = 0.743, determination coefficient of independent validation; RPD = 1.91, residual prediction deviation), SPA-MLR (R^2_{CV} = 0.709, R^2_{Val} = 0.747, RPD = 1.97) and RFR (R^2_{CV} = 0.714, R^2_{Val} = 0.783, RPD = 2.16) models with leaf-canopy d4 reflectance outperformed their corresponding models with leaf or canopy reflectance. We conclude that the wavelet-based coupling of leaf and canopy reflectance spectra has great potential in the accurate estimation of foliar N concentration. This proposed strategy helps to understand the spectral details of vegetation at a plot scale, providing the potential for improving the plot-based estimation of plant nutrients in grassland, precision agriculture or forestry.

1. Introduction

Foliar nitrogen (N) is indispensable in regulating the photosynthesis, respiration and productivity of vegetation through its strong relation with protein and chlorophyll (Yoder and Pettigrew-Crosby, 1995; Ollinger and Smith, 2005), and it is also one of the key factors limiting ecosystem function and health (Ramoelo et al., 2015). Remote sensing techniques have been continuously employed to advance the understanding of the regulatory role of foliar N in agriculture, forest or grass ecosystems in the past four decades (Thomas and Oerther, 1972; Tsay et al., 1982; Filella et al., 1995; Martin et al., 2008; Pullanagari et al., 2016), providing valuable information on planning and management for farmers, standards setters, government agencies and regulators.

Since Thomas and Oerther (1972) first explored the relationship between foliar N concentration and laboratory-based leaf reflectance of the sweet pepper, numerous researchers developed and improved the methodology, theory and application of the remotely sensed retrieval of foliar N (Tsay et al., 1982; Filella et al., 1995; Ollinger and Smith, 2005; Martin et al., 2008; Clevers and Kooistra, 2012; Pellissier et al., 2015; Ramoelo et al., 2015; Pullanagari et al., 2016). Previous studies were mainly carried out from the perspectives of an observing scale (leaf, canopy and landscape), plant species (single and multiple), modeling technique (univariate regression, multivariate regression and radiative transfer model) and the influencing factor of retrieval accuracy (e.g., phenology, geology, topography, soil type, water and fire). The fundamental mechanism for the retrieval of foliar N is associated with the rotation, bending and stretching of primary constituents (e.g., C—H, N—H, O—H, C—N and C—C bonds) of biochemicals in plant leaves (Curran, 1989; Mutanga et al., 2005); this process exerts a decisive impact on the optical properties of the leaf or canopy (Abdel-Rahman et al., 2010), providing a physical basis for correlating foliar N concentration with leaf or canopy reflectance.

It is well known that leaf reflectance is primarily dominated by water content, leaf structure and the concentration of plant biochemical components (e.g., pigments, proteins, N, cellulose, lignin and starch) (Guyot et al., 1992), while canopy reflectance is mainly governed by

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leaf reflectance, leaf area index, canopy architecture, soil background, atmospheric water absorption, viewing geometry and solar zenith angle (Jackson and Pinter, 1986; Asner et al., 2000). Given the intrinsic difference between leaf and canopy reflectance, several studies compared their performances in retrieving foliar biochemical concentrations at leaf and canopy scales (Daughtry et al., 2000; Doughty et al., 2011; Bian et al., 2013; Schlemmer et al., 2013); however, it is difficult to draw a consistent conclusion as to which estimation result is better, considered at a leaf or canopy scale.

The leaf reflectance can reflect the fundamental spectral features of vegetation, but it lacks the spectral information of three-dimensional structure; the canopy reflectance can cover the shortage of the leaf reflectance, but it is easily influenced by several external factors (e.g., soil and atmosphere) (Yoder and Pettigrew-Crosby, 1995; Abdel-Rahman et al., 2010; Bian et al., 2013). Besides, the known absorption features of N within leaf or canopy reflectance spectra are often not sensitive or recommended in the accurate estimation of foliar N concentration (Abdel-Rahman et al., 2010, 2013; Yao et al., 2010; Pellissier et al., 2015). Some researchers attempted to couple leaf and canopy reflectance using the PROSAIL radiative transfer model to incorporate the leaf optical properties and other influencing factors, such as canopy architecture and leaf area index (Botha et al., 2007); however, the spectral details of a sampling plot affected by these factors are barely captured. In most cases, the reflectance of vegetation at a sampling plot is often represented by the leaf, canopy or pixel-based imagery reflectance alone; however, due to the spatial heterogeneity and spectral variability of vegetation within different subplots, leaf or canopy reflectance alone barely reflects the actual spectral information of vegetation at a plot scale. To date, few efforts have been made to develop the potential reflectance spectra of vegetation at a plot scale based on the coupling of leaf and canopy reflectance spectra.

Due to the good ability of magnifying spectral details of leaf or canopy reflectance spectra, discrete wavelet transform (DWT) has been successfully used in the quantification of foliar chlorophyll (Blackburn and Ferwerda, 2008) and heavy metal concentrations (Liu et al., 2011; Wang et al., 2015a). The reconstructed reflectance spectra derived from DWT can reflect the detailed and subtle spectral signatures potentially associated with trace elements (e.g., copper) in plant leaves (Liu et al., 2011; Wang et al., 2015a), and they were also applied in distinguishing diffe'rent plant species (Koger et al., 2003). Hence, it is theoretically possible to couple the reconstructed leaf and canopy reflectance to integrate the spectral details potentially linked to vegetation parameters such as foliar N concentration, leaf structure or canopy architecture.

This study aimed to employ DWT to develop the potential spectral details of vegetation at a plot scale by coupling the reflectance spectra at the leaf and canopy scales and to explore their possibilities in estimating foliar N concentration. The wavelet-based coupling of leaf and canopy reflectance spectra may provide new insight into understanding the plot-based spectral features of vegetation and further advance the real-time monitoring of biochemical components (e.g., chlorophyll, phosphorus and water) of vegetation at a plot scale.

2. Materials and methods

2.1. Study area and field sampling

The study area is located in Poyang Lake (28°52′21″–29°06′46″ N, 116°10′24″–116°23′50″ E), which is the largest freshwater lake in China. *Carex* (*C. cinerascens*) is one of the dominant grass species in this region, and it is the main food source of some over-wintering birds, such as the swan goose (*Anser cygnoides*) and white-fronted goose (*A. albifrons albifrons*) (Zhang and Lu, 1999).

To obtain a large variation in foliar N concentrations, two field surveys were carried out from 4 to 7 December 2012 (vegetative stage, $n = 66$) and 10 to 15 April 2013 (heading stage, $n = 71$). In each field survey, nine sites were randomly selected within large areas of *Carex* biomes. At each site, four to eight plots (1 × 1 m) were randomly selected to maintain at least 30 m between any two plots. The canopy height of *Carex* varied from 14 to 60 cm, and the leaf inclination varied from 20° to 80°; there were bare soils seen from the top of short *Carex* biomes (average canopy height < 25 cm), while there was nearly 100% coverage from the top of tall *Carex* biomes (average canopy height > 25 cm). At each plot ($n = 137$), the longitude and latitude coordinates were obtained using a global position system receiver (Garmin Ltd., Lenexa, KS, USA); canopy reflectance spectra were collected (see Section 2.2); five subplots (0.25 × 0.25 m) in the center and four corners were harvested by clipping leaves 5 cm above the ground and merged; and one-third of the fresh merged leaves were immediately placed into a labeled sample bag for laboratory-based leaf reflectance measurement (see Section 2.2) and chemical analysis.

2.2. Canopy and leaf reflectance measurement

With an ASD FieldSpec 3 portable spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO, USA), the canopy reflectance spectra of *Carex* were measured at each plot during field sampling under clear skies from 10:00 to 14:00. The spectroradiometer covers a spectral range of 350–2500 nm with a sampling interval of 1.4 nm over 350–1000 nm and 2 nm over 1000–2500 nm, and the readings are interpolated with 1 nm by the onboard software. Prior to each spectral measurement, a white (barium sulfate, $BaSO_4$) Spectralon panel (10 × 10 inch) was used to calibrate the instrument and convert the measured spectral radiance into reflectance. The fiber optic sensor with a field of view of 10° was pointed at the center of each plot at the nadir position from approximately 1 m height, resulting in a 17.5 cm in diameter for the ground field of view without bare areas. Ten successive spectra were collected for each spectral measurement, and the measured values were averaged as the final spectrum.

Leaf reflectance measurements were made with the collected fresh leaves using the same spectroradiometer in a dark laboratory, in which the illumination conditions can be controlled and the adverse effect of stray light on leaf reflectance can be reduced. The leaves had a width of approximately 0.2–0.5 cm, thus the leaf reflectance was not conveniently measured with a single leaf using ASD plant probe and leaf clip. For each sample, the leaves were stacked six layers deep on a dark utensil (10 × 10 cm) according to the measurement strategy given by Datt (1998) and Coops et al. (2004), because single leaf layer could hardly provide complete coverage of the utensil, while a stack of six layers provided the maximum reflectance and could be used to obtain the reflectance from a layer of infinite optical thickness (Datt, 1998). Compared with the reflectance using single leaf or single layer leaves, the reflectance using stacked leaves might better combine with canopy reflectance in reflecting the spectral details at a plot scale, because canopy reflectance contains spectral information related to multiple layers of leaves. The difference among the three types of leaf reflectance lies in the magnitude of reflectance, without significantly affecting the coupling with canopy reflectance and the estimation accuracy of N concentration.

For each sample, the stacked leaves were illuminated with a 50 W halogen lamp (Analytical Spectral Devices, Inc., Boulder, CO, USA), which was placed at a 40 cm distance from the target and at 15° zenith angle incidence; the fiber optic with a 25° field of view was positioned in a pistol and mounted on a tripod 15 cm above the center of the target, providing a viewing area with 6.65 cm in diameter; a calibrated white Spectralon panel was systematically measured before the spectral measurement; and ten successive measurements were performed and averaged as the final spectrum.

2.3. Spectra pre-processing

Both leaf and canopy reflectance spectra (350–2500 nm, $n = 137$) were first reduced to the region of 400–1350 nm (named “original