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Examining view angle effects on leaf N estimation in wheat using field reflectance spectroscopy

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ABSTRACT

Real-time, nondestructive monitoring of crop nitrogen (N) status is a critical factor for precision N management during wheat production. Over a 3-year period, we analyzed different wheat cultivars grown under different experimental conditions in China and Canada and studied the effects of viewing angle on the relationships between various vegetation indices (VIs) and leaf nitrogen concentration (LNC) using hyperspectral data from 11 field experiments. The objective was to improve the prediction accuracy by minimizing the effects of viewing angle on LNC estimation to construct a novel vegetation index (VI) for use under different experimental conditions. We examined the stability of previously reported optimum VIs obtained from 13 traditional indices for estimating LNC at 13 viewing zenith angles (VZAs) in the solar principal plane (SPP). Backscattering direction showed better index performance than forward scattering direction. Red-edge VIs including modified normalized difference vegetation index (mND705), ratio index within the red edge region (RI-1dB) and normalized difference red edge index (NDRE) were highly correlated with LNC, as confirmed by high R^2 determination coefficients. However, these common VIs tended to saturation, as the relationships strongly depended on experimental conditions. To overcome the influence of VZA on VIs, the chlorophyll- and LNC-sensitive NDRE index was divided by the floating-position water band index (FWBI) to generate the integrated narrow-band vegetation index. The highest correlation between the novel NDRE/FWBI parameter and LNC ($R^2 = 0.852$) occurred at $-10°$, while the lowest correlation ($R^2 = 0.745$) occurred at 60°. NDRE/FWBI was more highly correlated with LNC than existing commonly used VIs at an identical viewing zenith angle. Upon further analysis of angle combinations, our novel VI exhibited the best performance, with the best prediction accuracy at 0° to $-20°$ ($R^2 = 0.838$, RMSE = 0.360) and relatively good accuracy at 0° to $-30°$ ($R^2 = 0.835$, RMSE = 0.366). As it is possible to monitor plant N status over a wide range of angles using portable spectrometers, viewing angles of as much as 0° to $-30°$ are common. Consequently, we developed a united model across angles of 0° to $-30°$ to reduce the effects of viewing angle on LNC prediction in wheat. The proposed combined NDRE/FWBI parameter, designated the wide-angle-adaptability nitrogen index (WANI), is superior for estimating LNC in wheat on a regional scale in China and Canada.

1. Introduction

Nitrogen (N) is one of the most important nutrient elements for crop growth and development. Effective monitoring of N status facilitates real-time diagnosis of plant growth, cultural management and productivity prediction during crop production (Raun and Johnson, 1999; Jiang et al., 2004). In particular, instantaneous, accurate estimation of in-season crop N status is critical for optimal growth and precise N management. With the rapid development of remote-sensing technology, spectral-based techniques can now be used to rapidly estimate crop N status, even at large scales (Peng and Gitelson, 2011; Ecarnot et al., 2013).

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Previous studies have demonstrated the potential of optical remote sensing for the assessment of plant N content using reflectance data, two- and three-band vegetation indices and several analytical techniques such as multiple linear regression and partial least squares (Feng et al., 2014; Ecarnot et al., 2013). Spectral indices using two to three sensitive wavebands are easily calculated using available computer software and are therefore commonly used to estimate aerial N status (Hatfield et al., 2008; Samborski et al., 2009). Li et al. (2014) proposed the three-band nitrogen planar domain index (NPDI) for the assessment of the aerial N concentration in wheat. The effectiveness of the canopy index was further confirmed by studying the relationship between red-edge and leaf N content (Feng et al., 2008). The canopy chlorophyll content index, which includes the red, red-edge and near-infrared bands, was subsequently proposed as a method to estimate wheat canopy N-related indicators (Rodriguez et al., 2006; Tilling et al., 2007; Fitzgerald et al., 2006; Perry et al., 2012). However, in previous studies these indices were typically evaluated from vertical observation only, and information on the influence of viewing angle is lacking. The accuracy and robustness of these indices may be inadequate to guide N application during critical crop growth stages due to the reflectance anisotropy of vegetation.

In previous investigations, most spectral remote sensing studies have been conducted almost at nadir. Therefore, the accuracy of spectral remote sensing techniques can be improved by selecting reasonable viewing angles, solar zenith angles and so on. Many studies have shown that multi-angle measurement is superior to vertical measurement for estimating the structural characteristics of ground objects (especially vegetation) (Shibayama and Wiegand, 1985). Indeed, combining spectral information and multi-angle information would improve the performance of indices for discriminating canopy structure (Mickelson et al., 2002; Huang et al., 2011). By taking advantage of multiple viewing angles, soybean varieties could be better distinguished (Kollenkark et al., 1982). The performance of indices in predicting yields and agronomic traits varies as a function of sensor viewing angle, as well as leaf area index (LAI) (Gemmell and McDonald, 2000; Aparicio et al., 2004). Furthermore, off-nadir viewing improves the performance of the indices for discriminating physiological characteristics (Gemmell and McDonald, 2000; Inoue et al., 2008). Galvão et al. (2013) demonstrated that the enhanced vegetation index (EVI) and photochemical reflectance index (PRI) are the most sensitive VIs for view/illumination geometry, even more so than the normalized difference vegetation index (NDVI), structure insensitive pigment index (SIPI) and vogelmann index (VOG). In light of the obvious anisotropy of the vegetation canopy, the new normalized hotspot-signature vegetation index (NHVI) (Hasegawa et al., 2010) and the hotspot-dark-spot index (HDS) (Pocewicz et al., 2007) were constructed to improve quantitative estimation of LAI. The canopy structural index (CSI) was also proposed as an indicator of canopy three-dimensional structure with the combination of normalized difference between dark-spot near infrared reflectance and hot-spot red reflectance (Sharma et al., 2013).

To date, some studies have been undertaken to utilize multi-angular remote sensing data, and some VIs have been derived to assess agronomic indicators (Mickelson et al., 2002; Galvão et al., 2009; Hasegawa et al., 2010; Huang et al., 2011). However, only a few indices has been systematically tested at the canopy level (Aparicio et al., 2004; Verrelst et al., 2008; Stagakis et al., 2010), especially their directional responses to plant nitrogen status. In addition, the selection of sensitive bands and viewing angles was often inconsistent when using multi-angular remote sensing datasets in previous investigations. Therefore, developing an untied inversion model would improve the practicality of monitoring crop production to reduce the effects of viewing angle on growth parameters prediction.

The objectives of this study were to: (1) analyze the effects of viewing angle on canopy reflectance and vegetation indices; (2) explore the effects of viewing zenith angle (VZAs) on LNC estimation in wheat using experimental data collected in China and Canada; (3) develop a new vegetation index that is sensitive to LNC and insensitive to the influence of VZA; and (4) compare the LNC prediction capability of the new model with that of existing indices. The ultimate goal was to develop a model for real-time monitoring and diagnosis of N nutritional status in wheat using multi-angular hyperspectral data. The wheat cultivars used in this study differed greatly in terms of phenology and were grown under greatly contrasting conditions in China and Canada.

2. Materials and methods

2.1. Experimental design

The experiments were conducted over a three-year period at two locations in Henan Province, China and two locations in Alberta, Canada. Different years, eco-sites, N rates, planting densities and cultivars of hexaploid winter wheat and spring wheat were utilized (Table 1).

2.2. Data acquisition

2.2.1. Canopy multi-spectral data acquisition

Canopy spectral reflectance data in China were collected at georeferenced points using an Analytical Spectral Devices (ASD) spectroradiometer (Boulder, CO, USA) fitted with a 25° field of view (FOV) fiber optic adaptor that could measure reflectance from 325 to 1075 nm with a sampling interval of 1.5 nm and a resolution of 3.5 nm. All canopy spectral measurements were taken from a height of 1 m above the canopy. The measurements were conducted on cloudless and windless days, from 10 am to 2 pm local time, in the solar principal plane (SPP). The SPP is formed by the line of the solar incident direction and a line perpendicular to the connecting line between the sun and the observed object. The VZA varied from −60° to +60° at intervals of 10° in each plot, which were defined as the forward direction (measured positively away from the Sun) and the backward direction (measured negatively into the Sun), with zero representing the nadir position. A 0.4×0.4 m $BaSO_4$ calibration panel was used under the same illumination conditions to convert the spectral radiance measurements to reflectance before and after vegetation measurements were taken. Ten scans were measured per point and averaged to produce the final canopy spectra.

Canopy spectral reflectance data in Canada were acquired with a goniometer System-2 (ULGS-2) multi-angle spectrophotometer (invented and created by Coburn and Noble at the University of Lethbridge) equipped with upwelling (UW) and Downwelling (DW) Ocean Optics USB-4000 spectrometers. An Ocean Optics USB-4000 spectrometer equipped with an 8° FOV barrel was mounted on the ULGS-2.0 to collect radiometric data from wheat samples over a range of 400–1000 nm. The sensor was placed at a height of 1.7 m above the canopy, directly on top of the zenithal arc. This equipment could sample 10 spectra in ⩽0.5 seconds with a spectral resolution of 2.8 nm. The measurements were conducted under clear sky conditions between 10:00 to 14:00 local time. Standard whiteboard emendation was performed promptly during the measuring process. The reflectance of a standard whiteboard was 1, thus measured spectra of target objects are given as dimensionless relative reflectance and relative transmittance. Ten scans