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Remote detection of canopy leaf nitrogen concentration in winter wheat by using water resistance vegetation indices from in-situ hyperspectral data

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ABSTRACT

Non-destructive monitoring of wheat nitrogen (N) status is essential for precision N management during wheat production. In this study, the quantitative correlation between leaf N concentration (LNC) and ground-based canopy hyperspectral reflectance in winter wheat was investigated. Field experiments were conducted for four years at different locations (Xinyang, Zhengzhou, and Shangshui) in China. Different N application rates, planting density, growth stages, and wheat cultivars were used. We developed a novel index (water resistance N index [WRNI]) that integrated the advantages of an index that minimizes water effects and an index sensitive to LNC. Data showed that the proposed combined index (WRNI), the ratio of the normalized difference red-edge index (NDRE) and floating-position water band index (FWBI) was both sensitive to LNC and resistant to variations in leaf water. Then, we optimized the bands of NDRE/FWBI to create an integrated narrow-band vegetable index $\left(\frac{(R735-R720)\times R900}{R\ \min(930-980)\times(R735+R720)}\right)$ to trace the dynamic changes in LNC in winter wheat. Our novel index and 15 selected common indices were tested for stability across growth stages, locations, years, treatments, cultivars, and plant types in estimating LNC in winter wheat. Six of the 16 previously determined indices performed well, and $R_{705}/(R_{717}+R_{491})$ and mND_{705} both showed the highest coefficients of determination ($R^2=0.832$ and 0.818, respectively) and the lowest root mean square error (RMSE = 0.401 and 0.417, respectively). When compared with the optimized common indices, the novel index WRNI was most closely correlated with LNC, and the corresponding linear equation yielded $R^2=0.843$ and RMSE = 0.382 across the whole 16 datasets; this further indicated a superior trace for LNC changes under heterogeneous field conditions. These models can accurately estimate LNC in winter wheat, and the novel index WRNI is promising for detecting LNC on a regional scale in heterogeneous fields under variable climatic conditions.

1. Introduction

Wheat is major food crop in China, and N is very important for the growth of wheat. Too little N can cause a decline in wheat production and lead to economic losses. However, too much N can cause environmental pollution (Dambreville et al., 2008; Sehy et al., 2003). Therefore, precision management and real-time and accurate evaluation of crop N status in the field are important (Raun et al., 2002). Therefore, information on in-season crop N status is critical for optimal growth and precise N management (Raun and Johnson, 1999; Zhang and Ma, 2000; Zhu et al., 2006).

The conventional method for measuring N by using plant tissue is effective for guiding N fertilizer use, but it is time-consuming and labor intensive. Several methods for the non-destructive prediction of plant N have been proposed, including leaf color charts, chloro-

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phyll meters, and chlorophyll fluorescence from individual leaves (Schächtl et al., 2005; Turner and Jund, 1994). With the development of remote sensing, and considering the relationship between N and chlorophyll in wheat (Boochs et al., 1990; Madakadze et al., 1999), spectral features of chlorophyll and red-edge bands have been used as indicators of wheat N (Lamb et al., 2002; Reyniers and Vrindts, 2006). Remote sensing of canopy reflectance has the potential to sample plant populations or communities rather than individual plants, and it could be used to rapidly monitor the growth status and spatial variability of wheat over a large area (Blackmer et al., 1996; Jongschaap and Booij, 2004; Tarpley et al., 2000). However, spectral reflectance of the plant canopy is affected by factors such as soil background structure, vegetation biophysical properties, and vegetation canopy, which impact the estimation accuracy of agronomic indices.

To reduce the impact of these factors, a number of vegetation indices have been developed to estimate N-related indicators by using remote sensing data for different types of crops. For instance, the normalized difference vegetation index (NDVI) calculated from combinations of two bands, red and near-infrared, is the most frequently used index. However, NDVI is easily saturated by a dense canopy, decreasing the sensitivity of NDVI to high physiological and biochemical contents of crops (Gitelson, 2004; Thenkabail et al., 2000). Therefore, the optimized soil adjusted vegetation index (OSAVI) was developed by adding a parameter to minimize the effects of the soil on crop canopy response (Rondeaux et al., 1996). On the scale for vegetation biophysical properties, atmospherically resistant vegetation index (ARVI) was proposed to eliminate the effect of atmosphere; ARVI takes advantage of the presence of the blue channel (Kaufman and Tanre, 1992). Compared with NDVI, the resistance of ARVI to atmospheric effects is better. On the canopy scale, modified normalized difference (mND_{705}) was developed, and it was proposed by adding R_{445} to the two-band vegetation indices, effectively reducing the impact of differences in leaf surface reflectance and improving the precision of pigment content estimation (Sims and Gamon, 2002). Usually there is an interaction between crop growth parameters. This multifactor interaction complexity leads to variability in the spectral reflectance of the canopy at different phonological stages, which encouraged some scholars to improve the estimation precision of the target index by using the method of parameter combination. For example, some scholars combined spectral parameters with agronomic parameters to improve the estimation accuracy of LNC and reduce the influence of agronomic parameters, such as mND705 × BDW (Jin et al., 2012). In addition, Haboudane et al. (2002) developed an index, transformed chlorophyll absorption in reflectance index (TCARI)/OSAVI, and the proposed index is both sensitive to chlorophyll content variations and resistant to variations in LAI and underlying soil background effects. The above-mentioned studies indicated that optimized algorithms have the potential for the effective evaluation of plant growth status to reduce the impact of multifactor interaction.

Interaction between water and N content is observed during crop growth. Therefore, we had to consider the effect of canopy moisture when assessing N content. Thus, in this study, we proposed a novel vegetation index that is both sensitive to N content variations and resistant to variations in moisture. The objectives of this study were to: (i) develop a novel index for monitoring LNC; (ii) compare the reliability of several common indices and the combined index for monitoring LNC under different field experiment conditions; (iii) quantify the relationships between LNC and the new index and determine the united equation for monitoring LNC; (iv) and test the performance of the newly designed index for monitoring LNC in winter wheat by using independent data. The anticipated outcome would help in improving the real-time monitoring of LNC in winter wheat, leading to the precise application of N fertilizers by using a remote-sensing approach.

2. Materials and methods

2.1. Experimental design

The experiments were conducted across three growth seasons at three locations in China. Different years, N rates, planting density, and cultivars of hexaploid winter wheat (Triticumaestivum L.) were investigated (Table 1). Experiments 1 and 2 were conducted in 2010–2012 at the experiment station of Xinyang Academy of Agricultural Sciences in Xinyang City (31°53′N, 114°32′E) with heavy clay soil. Experiments 3–6 and 9 were conducted in 2011–2014 at the experiment station of Henan Agricultural University located in Zhengzhou City (34°51′N, 113°35′E) with fluvo-aquic soil. Experiments 7 and 8 were conducted in 2013–2014 at Shangshui Farm in Zhoukou City (33°33′N, 114°37′E), with lime concretion black soil. Two cultivation treatments for N rates and planting density were conducted in four consecutive seasons from November 2010 to June 2014, with a low rainfall season in 2010–2012 at the Xinyang site and in 2011–2013 at the Zhengzhou site and a normal rainfall season in 2011–2012 at the Xinyang site and in 2013–2014 at the Zhengzhou and Shangshui sites. Five winter wheat cultivars were divided into two types: Erect cultivars, namely, Yumai 49–198, Yumai50, and Zhoumai18, and horizontal cultivars, namely, Zhengmai 9694 and Yumai34. The vegetative period consisted of jointing and booting stages, and the reproductive period consisted of heading, initial-filling, and mid-filling stages. A randomized complete block design and a factorial arrangement of treatments were used with three replications. Other management procedures were according to the local standard practices for winter wheat production.

2.2. Measurement of canopy reflectance

All canopy spectral measurements were obtained from a height of 1 m above the canopy (height of wheat was 70–80 cm at maturity) under clear sky conditions between 10:00 and 14:00 (Beijing local time), using an ASD Field Spec Pro spectrometer (Analytical Spectral Devices, USA). The sensor was fitted with 25° field-of-view fiber optics operating in the 325–1075 nm spectral region with a sampling interval of 1.6 nm. A 40 cm × 40-cm $BaSO_4$ calibration panel was used to calculate black and baseline reflectance. To minimize the effects caused by the sky and field conditions, spectral measurements were obtained from 10 sites in each plot and averaged into a single spectral sample. For each experiment, data were obtained on several different dates at major growth stages of wheat (Table 1).

2.3. Measurement of agronomic parameters

Samples for measuring leaf weight and leaf nitrogen (N) concentration (LNC) were collected immediately after canopy spectral measurement. In addition to the roots, the wheat was cut and fresh weights (FWs) were recorded in 0.2 m^2 (0.5 m long in 2 rows; spacing interval, 20 cm). Each plant was then dried at 70 °C to constant weight, and then dry weight (DW) was recorded. The dry plant samples was then ground and measured using a dry combustion method with a Dumas Elementary Analyser (Macro-N, Foss Heraeus, Hanau, Germany) (Schepers et al., 1989). Leaf water content was simultaneously determined in Experiments 1 and 2. Then, the leaves were dried at 65 °C until constant weight was achieved.