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Exploring new spectral bands and vegetation indices for estimating nitrogen nutrition index of summer maize

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ABSTRACT

Accurately and timely diagnosis of plant nitrogen (N) status is imperative for N fertilization management and yield prediction of summer maize. This study was aimed to identify the most sensitive/appropriate spectral band combinations to estimate the N nutrition index (NNI) by comprehensive analyses on canopy spectral reflectance from visible to near-infrared light, to develop the optimum vegetation indices for NNI during V6-V12 growth period, and to validate the regression models for estimating NNI of summer maize by comparing the two methods (direct and indirect) to determine the most appropriate method for practical use. Five multi-locational and multi-N rates (0–320 kg ha^{-1}) field experiments were conducted during three growing seasons (2015, 2016 and 2017) using five summer maize cultivars. The measurements regarding canopy spectral reflectance, plant biomass, and plant N concentration were taken at critical stages of summer maize under the various N treatments. Comprehensive analyses on the different regression models of NNI for normalized difference spectral index (NDSI) and ratio spectral index (RSI) composed of any two bands between 325 and 905 nm of summer maize were made by using the reduced precise sampling method. The NNI values in the present study ranged from 0.68 to 1.15 under different N treatments. The most sensitive spectral bands were located at 710 nm (red edge band) and 512 nm (visible light band) and the optimum spectral vegetation index for estimating NNI was NDSI (R_{710}, R_{512}). The linear regression model between NDSI (R_{710}, R_{512}) and NNI was NNI = 0.95 NDSI (R_{710}, R_{512}) + 0.14. Additionally, the soil-adjusted vegetation index (SAVI) was used to correct NDSI(R_{710}, R_{512}), and the performance of the linear regression model was best when the parameter L (soil-brightness correction factor) of SAVI (R_{710}, R_{512}) was 0.05. The performances of the direct and indirect NNI estimation methods were compared. The validation results showed that the performance of the newly developed vegetation indices (NDSI (R_{710}, R_{512}) and SAVI (R_{710}, R_{512})$_{(L=0.05)}$) was the best with the relative root mean square error (RRMSE) values ranging from 11.4% and 13.1% in the direct method; while the performance of the existing vegetation indices (Ratio Vegetation Index II and modified SAVI) were best with RRMSE value of 16.9% in the indirect method. It was concluded that both the direct and indirect methods can be used to estimate NNI of summer maize, but the construction of the newly developed vegetation indices was easier in the direct method. The projected results will provide a technical basis for potential application of remote sensing technology for monitoring and diagnosis of plant N nutrition in summer maize production.

1. Introduction

Crop nitrogen (N) status is a very important index for evaluating crop growth, yield, and quality. To achieve a higher grain yield, farmers usually apply more N to the field than required by summer maize during the growing season in China. Cui et al. (2008) reported that the mean N application rate (249 kg ha^{-1}) for summer maize exceeds the amount of N required to achieve maximum grain yield. Excessive N input not only reduces the farmers earning but also causes groundwater pollution and greenhouse gas emission (Brauns et al., 2016). Therefore, it is indispensable to optimize N management to reduce the amount of N input and improve N use efficiency.

To optimize N management during crop growth, it is necessary to have an accurate and timely understanding of crop N status (Ata-Ul-

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Karim et al., 2017a). In recent years, N nutrition index (NNI), the ratio between the actual plant N concentration (PNC) and plant critical N concentration (N_c) has been considered as a reliable index for diagnosing crop N status (Zhao et al., 2017). The N_c concentration is defined as the minimum N concentration required for maximum crop growth (Justes et al., 1994). NNI values of 1 indicate the optimum plant N status, while NNI > 1 and NNI < 1 indicates excess and deficient N nutrition, respectively. The traditional method of NNI calculation requires considerable time and destructive sampling in the field (Zhao et al., 2016), which hinders its application on large scale. Mistele and Schmidhalter (2008) demonstrated the possibility to rapidly and non-destructively assess the NNI by remote sensing technologies.

Analyzing the reflectance features of the canopy spectrum to estimate plant N status during crop growth is one of the most important aspects of agricultural remote sensing (Li et al., 2014). Several vegetation indices (ratio, normalization, and derivative) and crop growth indices (e.g., crop N/chlorophyll concentration, crop N/chlorophyll accumulation, leaf area index (LAI), and biomass) have been established for diagnosing crop N status worldwide by screening the sensitive bands of the canopy reflectance spectrum (Schlemmer et al., 2013; Gnyp et al., 2014; Jay et al., 2016). Yet, each growth index only represents part of the information on crop growth condition, which can be easily affected by crop growth stage, canopy structure, density, and field microclimate (Wang et al., 2014). Additionally, growth indices are difficult to employ for estimating the plant N deficit and its extent qualitatively and quantitatively, causing limitations for diagnosing plant N status (Wang et al., 2014). NNI has an advantage over singular growth indices (LAI, biomass, and crop N/chlorophyll concentration) in diagnosing crop N status qualitatively and quantitatively since it is derived from plant N_c concentration and requires two indices (biomass/LAI and PNC) (Ata-Ul-Karim et al., 2017a; Zhao et al., 2017). To date, few studies have been conducted to estimate the NNI value by using existing vegetation indices. The methods used in these studies can be classified into two types; indirect method and direct method. The indirect method estimates NNI by predicting actual N concentration and biomass by vegetation indices. Chen et al. (2009) predicted NNI of spring maize by combining a double-peak canopy nitrogen index (DCNI) to estimate N concentration, and a red-edge triangular vegetation index (RTVI) to estimate biomass in Canada. Cilia et al. (2014) predicted NNI of spring maize through spectral images by using a chlorophyll concentration index (CCI) to estimate N concentration, LAI, and biomass in Italy. However, these studies used vegetation indices related to leaf N concentration, leaf biomass, LAI, and chlorophyll content, and Cilia et al. (2014) utilized actual leaf N concentration to calculate NNI instead of actual PNC. The direct method estimates NNI by developing a regression model between NNI and the existing spectral indices. Mistele and Schmidhalter (2008) have estimated the NNI of winter wheat directly by using the index of red edge inflection point (REIP) in Germany. In China, Liang and Liu (2010) have used the combination of three existing vegetation indices to estimate NNI of summer maize. However, the spectral bands of the existing vegetation indices are only sensitive to a particular growth index (e.g., N concentration or biomass), and can be easily affected by soil background and growth stage. Moreover, the structure of some indices is very complicated and impractical. An exclusive and simple vegetation index to estimate NNI is lacking.

The newly emerged hyperspectral remote sensing has the characteristics of high resolution (< 10 nm) and successive changes in spectral curves at each band to acquire more band combinations and parameter types, ultimately providing more accurate information on spectral reflectance as affected by PNC, biomass, LAI and other growth indices (Yao et al., 2010). Previous hyperspectral studies on PNC, plant N accumulation, LAI and biomass in maize (Quemada et al., 2014; Cilia et al., 2014; Xia et al., 2016) indicated that hyperspectral remote sensing can accurately estimate plant growth status of maize. To date, no attempt has been made to systematically analyze the combination of the hyperspectral bands (from visible light to near infrared) to the sensitivity of NNI, which might result in some sensitive characteristic bands to NNI that have yet to be exploited. Therefore, the objectives of this study were to identify the most sensitive/appropriate hyperspectral band combinations to estimate the NNI by comprehensive analyses on canopy spectral reflectance from visible to near-infrared light, to develop the optimum vegetation indices for NNI during V6-V12 growth period, and to validate the regression models for estimating NNI of summer maize by comparing the two methods (direct and indirect) for establishing the most appropriate method for practical use. The results will provide a technical basis for potential application of hyperspectral remote sensing technology to monitor and diagnose the plant N nutrition in summer maize production.

2. Materials and methods

2.1. Experimental design

Five varied N rate (0–320 kg ha^{-1}) field experiments were conducted during 2015, 2016 and 2017 seasons of summer maize using five summer maize cultivars at two sites, (Xinxiang, 35°18′N, and 113°52′E; Qinyang, 35°08′N, and 112°92′E) located in China (Table 1). A detailed description of site characteristics, experimental design, crop management and weather condition is provided in Tables 1 and 2. Soil samples were collected from the 0–20 cm soil layer before summer maize planting. The samples were air-dried, sieved, and then used to measure organic matter (Walkley-Black titration method), total N (traditional Kjeldahl method), Olsen-P (0.05 mol L^{-1} $NaHCO_3$), and NH_4OAc-K^+ (1 mol L^{-1} ammonium acetate at pH 7), respectively (Nelson and Sommers, 1982; Bremner and Mulvancy, 1982; Olsen et al., 1954; van Reeuwijk, 1992). Each experiment was arranged in a randomized complete block design with three replicates. The size of each plot was 60 m^2 (6 m × 10 m) in all the experiments. 50% of the total N fertilizer was applied before sowing while the remaining 50% was applied at the V6 stage. All replicates received adequate quantities of triple superphosphate (150 kg P_2O_5 ha^{-1}) and potassium chloride (120 kg K_2O ha^{-1}) before sowing. Summer maize was over-seeded with hand planters and then thinned at the seedling stage to a stand of 75,000 plants ha^{-1} with a row spacing of 60 cm in both seasons. Additional crop management practices were in accordance with local agricultural practices. The field was irrigated (40 mm) to ensure emergence after sowing. Due to adequate rainfall, it was not necessary to irrigate the field during the growth period of summer maize. No obvious water, pest, or disease stress was observed during the growing seasons. The only limiting factor was N fertilizer application.

2.2. Sampling and measurement

Six plants per plot were harvested at different growth stages to determine plant biomass and PNC. The sampling stages for each experiment are presented in Table 1. For each sampling date, the plants were severed at ground level and separated into stems and leaves. Each part was oven dried at 80 °C until a constant weight to measure corresponding biomass (dry matter, t ha^{-1}). The dried parts were ground, passed through a 1-mm sieve, and stored in plastic bags for chemical analysis. The N concentration of each plant part was determined by using the traditional Kjeldahl method (Bremner and Mulvancy, 1982). PNC was calculated as the product of biomass and N concentration in each part.

Spectral reflectance of plant canopies of summer maize was measured by using a portable spectrometer (FieldSpec Handheld 2; Analytical Spectral Devices (ASD), USA) at a height of 0.5 m above the canopy in the middle rows of each plot under clear sky conditions between 10:00 and 14:00 h. The spectrometer has a spectral range of 325–1075 nm, a spectral resolution of 3.5 nm, a sampling interval of 1.4 nm, and a field of view of 25°. Each measurement of canopy spectral