Computers and Electronics in Agriculture 151 (2018) 185–195

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Diagnosis of nitrogen status in winter oilseed rape (*Brassica napus* L.) using *in-situ* hyperspectral data and unmanned aerial vehicle (UAV) multispectral images

Shishi Liu, Lantao Li, Wenhan Gao, Yukun Zhang, Yinuo Liu, Shanqin Wang, Jianwei Lu*

College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China
Key Laboratory of Arable Land Conservation (Middle and Lower Reaches of Yangtze River), Ministry of Agriculture, Wuhan 430070, China

ARTICLE INFO

Keywords:
Nitrogen nutrition index (NNI)
Vegetation indices
Image texture metrics
Unmanned aerial vehicle (UAV)
In situ hyperspectral data
Multispectral images

ABSTRACT

This study aimed to investigate whether the optimal vegetation indices (VIs) derived from the *in situ* hyperspectral data to estimate the nitrogen nutrition index (NNI) can also be used at the local scale using unmanned aerial vehicle (UAV) multispectral images, and whether texture metrics derived from UAV images could improve the remote estimation of the NNI in winter oilseed rape. Three field experiments with different N fertilization levels were conducted in two sites in Hubei Province, China. The mechanistic and empirical methods were both employed to estimate NNI. With the *in situ* hyperspectral data, the empirical method based on structural VIs (R^2 is about 0.70) or the photochemical reflectance index (PRI) ($R^2 = 0.73$) provided more accurate estimations of NNI than the mechanistic method did ($R^2 = 0.62$). Although most of the studied VIs were strongly correlated with the NNI, they had different responses to the NNI at the low N fertilization and the optimal to excessive N fertilization rates. For the UAV multispectral images, the mean VI of all pixels within the region of interest (ROI) (referred to VI_mixed) outperformed the mean VI of vegetation pixels within the ROI (referred to VI_pure). The mean normalized difference vegetation index (NDVI_mixed), the modified soil adjusted vegetation index 2 (MSAVI2_mixed), and the red edge chlorophyll index ($CI_{red\ edge}$_mixed) of all pixels within the ROI yielded more accurate NNI estimates than the other VIs. Furthermore, the stepwise multiple linear regression models with VIs and texture metrics of VIs provided more accurate NNI estimations than the models based solely on VIs. Results of this study suggested the great potential of UAV multispectral images in monitoring the crop N status at local scales.

1. Introduction

Winter oilseed rape (*Brassica napus* L.) is one of the most important oilseed crops in the world. The Yangtze River Basin in China accounts for one-fifth of the rapeseed yield and cultivation area in the world (FAOSTAT, 2014). Winter oilseed rape in this area is usually grown in rotation with rice, cotton or soybeans, leading to the limited supply of soil nutrients (Degenhardt and Kondra, 1981; Zhang et al., 2006). To maintain the high yields under an intensive cropping system, large amounts of nitrogen (N) fertilizer are applied to the field. Excessive N are retained by the soil and/or lost through gasification, leaching and runoff, leading to serious environmental problems such as greenhouse gas emissions and water contamination (Zhu and Chen, 2002; Zhao et al., 2007). The accurate and rapid diagnosis of the N status of winter oilseed rape in the Yangtze River basin is important to ensure both the yield and the quality while minimizing environmental damages caused by the excessive application of N fertilizers.

Remote sensing is a unique tool for providing information linked to plant N status in a rapid, cost-effective, and non-destructive way (Inoue et al., 2012; Chen et al., 2010; Pellissier et al., 2015; Feng et al., 2016). Although N absorption features at 1510 nm, 1730 nm, 1940 nm, 1980 nm, 2060 nm, 2180 nm, 2240 nm, 2300 nm, and 2350 nm were discovered in the spectra of dried ground leaves, these absorption features cannot be used to remotely estimate the N content/concentration in green leaves, because strong water absorption (centered at 1450 and 1940 nm) in the shortwave infrared region obscures N absorption features (Kokaly and Clark, 1999). The close relationship between chlorophyll and the N content in plants is the foundation of most remote

Acronyms: DM, dry matter; LAI, leaf area index; NNI, nitrogen nutrition index; PNC, plant nitrogen concentration; R^2, the determination coefficient; RMSE, root mean square error; ROI, region of interest; SMRL, stepwise multiple linear regression; UAV, unmanned aerial vehicle; VI, vegetation index

* Corresponding author at: College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China.
E-mail address: lunm@mail.hzau.edu.cn (J. Lu).

https://doi.org/10.1016/j.compag.2018.05.026
Received 3 December 2017; Received in revised form 24 May 2018; Accepted 27 May 2018

sensing approaches that assess the plant N status (Kokaly et al., 2009; Vos and Bom, 1993). Vegetation indices (VIs) based on red, red edge, and near infrared spectral bands have been shown to be effective predictors of chlorophyll as well as the N content in plants (Solari et al., 2008; Schlemmer et al., 2013; Clevers and Gitelson, 2013).

Leaf and canopy N concentration decrease through the growth season as biomass increases until senescence, and hence they are not the optimal indicators of the plant N status (Chen et al., 2010; Rathke et al., 2006). The nitrogen nutrition index (NNI) was developed to diagnose plant N status in order to adjust N fertilization (Lemaire and Meynard, 1997). The NNI is calculated as the ratio of the measured plant nitrogen concentration (PNC) to the critical PNC at a given biomass level, wherein the critical PNC is the minimum N concentration required for the maximum biomass production during the vegetative period (Lemaire et al., 2008). The potential of estimating the NNI with remotely sensed data have been explored for wheat (Mistele and Schmidhalter, 2008; Chen, 2015; Cao et al., 2015; Jin et al., 2015), maize (Cilia et al., 2014; Xia et al., 2016), and rice (Yao et al., 2014; Huang et al., 2015; Huang et al., 2017). NNI can be estimated using the mechanistic method or the empirical method (Lemaire et al., 2008). The mechanistic method estimates NNI based on a known critical N curve that are derived from massive ground experiment data, and PNC and biomass that are estimated with remote sensing data. The empirical method builds the regression models between the NNI and reflectance measurements or VIs. Studies have found that several VIs, such as the normalized difference vegetation index (NDVI), the red edge inflection point (REIP), and the modified green soil adjusted vegetation index (MGSAVI), are closely related with NNI (Mistele and Schmidhalter, 2008; Cao et al., 2015; Chen, 2015).

Most investigations on the remote diagnosis of the crop N status use *in situ* hyperspectral data. Whether results derived from *in situ* hyperspectral reflectance can be applied to large areas using aerial or satellite data still requires additional research (Huang et al., 2015; Huang et al., 2017). With the recent development of low-cost compact imaging spectrometers and unmanned aerial vehicle (UAV), a UAV-based multispectral imaging system can provide a more flexible and efficient alternative to monitoring crops in large areas. Attempts have been made to assess the crop N status with the UAV-based multispectral imaging systems. Miao et al. (2009)'s study combined chlorophyll meter readings with aerial hyperspectral images to evaluate the maize N status. Cilia et al. (2014) applied aerial hyperspectral images to estimate the maize NNI using the mechanistic method. Nigon et al. (2015) predicted the N stress in potatoes using aerial hyperspectral images. Due to the high spatial resolution of UAV images, their texture features of UAV images may also be useful for crop monitoring. The image texture measures the heterogeneity in the tonal values of pixels within a defined area of an image (Champion et al., 2008; Wood et al., 2012). Remotely sensed image textures have been used for characterizing vegetation structure and as the input for vegetation classifications (Herold et al., 2004; Wood et al., 2012; Dube and Mutanga, 2015). However, to our knowledge, texture features of UAV images have not been used to assess the crop N status.

The objectives of this study are to (1) study whether the optimal VIs derived from the *in situ* hyperspectral data could be used in the UAV multispectral images to estimate the NNI in winter oilseed rape, and (2) to investigate if the textural metrics derived from UAV multispectral images could improve the estimation of the NNI.

2. Materials and methods

2.1. Study sites and experimental design

One field experiment was conducted during 2014–2015 in Wuxue (30°06′ N, 115°35′ E) and two field experiments were conducted during 2015–2016 and 2016–2017 in Shayang (30° 43′ N, 118° 18′ E) (Fig. 1, Table 1). Both study sites are located in Hubei Province, China, and have a humid sub-tropical monsoon climate. The rapeseeds of cultivar "Huayouza No. 9" were used in our study. In the three experiments, rapeseeds were first sown in the prepared seedbeds in September using high fertility soils. The seedlings were then transplanted into the tilled field in October, when seedlings had five to six leaves, at a density of 112,500 plants ha^{-1}. The soil fertility status in the top 20 cm soil layer measured before the experiments are shown in Table 2. The soil pH value was measured using a pH electrode at a water/soil ratio of 2.5:1; organic matter was determined using the chromic acid titration method; the total N was determined using the Kjeldahl acid-digestion method; the Olsen-P value was measured using the NaHCO3 method; the available K was measured using a flame photometer method; and the available B was determined using the curcumin colorimetric method (Bao, 2000).

During 2014–2015, the experimental site was divided into 24 plots randomly assigned to eight treatments with three replications for each treatment. During 2015–2016, the site was divided into 27 plots, randomly assigned to nine treatments with three replications for each treatment. For Experiments 1 and 2, the area of each plot was 30 m^2 (15.0 m × 2.0 m), and the furrow between two plots was 0.5 m in width. During 2016–2017, the site was divided into 21 plots, randomly assigned to seven treatments with three replications for each treatment. The area of each plot was 10 m^2 (5.0 m × 2.0 m), and the furrow between two plots was 0.5 m in width. The N fertilization treatments for each experiment are shown in Table 2.

Urea containing 46% N was used as the N fertilizer in all experiments (Table 3). According to the previous study on the yield response to N fertilizer using data of 1457 site-year on-farm experiments in the Yangtze River Basin (Li et al., 2015), N0 – N135 were low N treatments, N180 – N240 were optimal N treatments, and N270 – N360 were excessive N treatments. The fertilizer rates of nutrients other than N were the same among the experiments, and they consisted of 750 kg P_2O_5 ha^{-1} (superphosphate, 12% P_2O_5), 200 kg K_2O ha^{-1} (potassium chloride, 60% K_2O), and 15 kg B ha^{-1} (borax, 10.8% B). The fertilizers were plowed into the topsoil as the base fertilizer before the seedlings were transported to the field.

2.2. Data

2.2.1. Vegetation sampling

Ground sampling campaigns were conducted during the vegetative period of winter oilseed rape (Table 1). The leaf area index (LAI) was measured using a plant canopy analysis instrument (SunScan, Probe type SS1, Delta-T Devices company, England). After the LAI and canopy spectra were measured, a 0.5 m * 0.5 m quadrat was randomly placed in each plot for three times. The number of winter oil seed rape specimens in the quadrat was counted, and the average value of three randomly placed quadrats was used to calculate dry mass (DM). Four plants from each plot were destructively sampled to measure the DM and PNC. The samples were weighed to obtain the fresh mass, cleaned, de-enzymed at 105 °C for 30 min, and later dried at 70 °C in an oven to a constant weight to obtain the DM. The above-ground DM in Mg ha^{-1} was calculated for each plot based on the number of winter oilseed rape specimens in the quadrat, and DM was weighed in the lab. 0.15-g sample of the DM was used to determine the PNC with the micro-Kjeldahl method (Yu et al., 2013). The samples were digested with H_2SO_4-H_2O_2, and then flow injection analysis (FIA, AA3, SEAL, Germany) was used to determine the PNC.

2.2.2. Ground-based spectroscopy

The canopy spectra were collected under sunny and cloudless conditions around midday (10:00–14:00) local time using the Analytical Spectral Devices Field Spec Pro spectrometer (ASD, Boulder, CO, USA). A fiber-optic sensor with a 25° field of view was placed 1 m above the canopy in a nadir position. A white spectralon reference panel was used for calibration before the canopy spectra were measured for each plot.