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Active canopy sensing of winter wheat nitrogen status: An evaluation of two sensor systems

Qiang Cao[a,b], Yuxin Miao[a,*], Guohui Feng[c], Xiaowei Gao[a], Fei Li[d], Bin Liu[a], Shanchao Yue[a], Shanshan Cheng[a], Susan L. Ustin[e], R. Khosla[f]

[a] *International Center for Agro-Informatics and Sustainable Development (ICASD), College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China*
[b] *National Engineering and Technology Center for Information Agriculture, Nanjing Agricultural University, Nanjing 210095, China*
[c] *Department of Agriculture, Qingfeng Farm, Hulin, Heilongjiang 158421, China*
[d] *College of Ecology and Environmental Science, Inner Mongolia Agricultural University, Hohhot 010019, China*
[e] *Center for Spatial Technologies and Remote Sensing (CSTARS), Department of Land, Air, and Water Resources, University of California, Davis, CA 95616, USA*
[f] *Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO 80523, USA*

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ABSTRACT

Crop canopy sensor based in-season site-specific nitrogen (N) management is a promising approach to precision N management. GreenSeeker sensor has previously been evaluated in North China Plain (NCP) for improving winter wheat (*Triticum aestivum* L.) N management. The Crop Circle ACS-470 is an active canopy sensor with three user-configurable wavebands. This study identified important vegetation indices that can be calculated from Crop Circle green, red edge and near infrared (NIR) wavebands for estimating winter wheat N status and evaluated their potential improvements over GreenSeeker normalized difference vegetation index (NDVI) and ratio vegetation index (RVI). Six field experiments involving different N rates and varieties were conducted in the Quzhou Experiment Station of the China Agricultural University from 2009 to 2012. The results indicated that best Crop Circle ACS-470 sensor vegetation indices could explain similar amounts of aboveground biomass variability in comparison with GreenSeeker sensor NDVI, but Crop Circle normalized difference red edge/green optimized soil adjusted vegetation index (NDRE/GOSAVI) and red edge chlorophyll index (CI_{RE}) were more sensitive to aboveground biomass (having lower noise equivalent) than GreenSeeker NDVI before and after biomass reached about 5000 kg ha^{-1}, respectively. The Crop Circle green difference vegetation index (GDVI) (R^2 = 0.60) and chlorophyll index (CI_G) (R^2 = 0.89) explained 53% and 7–11% more variability in plant N concentration and uptake than GreenSeeker indices, respectively. The Crop Circle green re-normalized difference vegetation index (GRDVI) (R^2 = 0.78) and modified green soil adjusted vegetation index (MGSAVI) (R^2 = 0.77) performed consistently better than GreenSeeker NDVI (R^2 = 0.47) and RVI (R^2 = 0.44) for estimating N nutrition index (NNI). We conclude that the three band user configurable Crop Circle ACS-470 sensor can improve the estimation of winter wheat N status as compared with two fixed band GreenSeeker sensor.

1. Introduction

Precision nitrogen (N) management aims to optimize N fertilizer inputs by considering both spatial and temporal variability of crop N demand and supply and has been regarded as a promising strategy to improve N use efficiency and protect the environment (Miao et al., 2007, 2011; Diacono et al., 2013). The success of this strategy, however, largely depends on the development of efficient technologies for real-time site-specific diagnosis of crop N status during the growing season and making N application recommendations accordingly.

Plant N concentration (PNC) and uptake (PNU) have been used as major indicators for assessing plant N status. However, optimum PNC depends on aboveground biomass. If two different plants have the same PNC but differ in aboveground biomass, it is possible that the plant with higher aboveground biomass is well supplied with N, whereas the one with lower biomass may be suffering from N deficiency (Lemaire et al., 1992). Plant N uptake is highly variable within a single year, between years, sites and crops, even when the N supplies from both the soil and additional fertilizer inputs are plentiful (Gastal and Lemaire, 2002). Various studies have reported

* Corresponding author. Tel.: +86 10 62732865; fax: +86 10 62731016.
E-mail addresses: ymiao@cau.edu.cn, ymiao2007@gmail.com (Y. Miao).

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that PNC decreases during the growth cycle in dense canopies (Greenwood et al., 1986; Ziadi et al., 2010b) and have a close non-linear relationship to the aboveground biomass, whatever the climatic conditions of the year, or the species and genotype (Lemaire et al., 2005). The critical N dilution curve, which describes the relationship between the aboveground biomass and critical N concentration, has been established for many plant species (Justes et al., 1994; Sheehy et al., 1998; Plénet and Lemaire, 1999; Ziadi et al., 2010a; Yue et al., 2012). The critical N concentration is defined as the minimum PNC necessary to achieve maximum aboveground biomass production (Greenwood et al., 1986, 1991). The critical N concentration information is incorporated in the N nutrition index (NNI) to indicate the relative plant N status (Greenwood et al., 1991; Lemaire et al., 1992; Lemaire and Gastal, 1997), which is calculated as the ratio of the measured N concentration and the critical N concentration. An NNI value greater than one indicates non-limiting N status, whereas a value less than one corresponds to N deficiency. However, these plant-based parameters are not suitable for practical applications across large areas, because measuring such parameters requires destructive plant sampling and chemical analysis, which are expensive, time-consuming and labor-intensive. Besides, only a few plants can be sampled in a large field and these may not accurately represent the N status and distribution across the entire field (Fitzgerald et al., 2010).

There has been increasing interest in using proximal and remote sensing technologies to estimate plant N status (Houlès et al., 2007; Mistele and Schmidhalter, 2008; Ziadi et al., 2008; Cao et al., 2013; Diacono et al., 2013). Leaf sensors, like chlorophyll meter (Debaeke et al., 2006; Prost and Jeuffroy, 2007; Ziadi et al., 2008; Cao et al., 2012) and Dualex sensor (Tremblay et al., 2012), have been used to diagnose crop N status. However, these measurements are still time-consuming with values being accurate only for the measurement spots (Blackmer et al., 1994) and making them difficult to apply for site-specific N management across large field or areas (Miao et al., 2009). On the other hand, crop canopy sensors are more efficient and promising (Yao et al., 2012; Cao et al., 2013). Mistele and Schmidhalter (2008) used a passive hyper-spectral canopy sensor to estimate NNI, achieving an overall average R^2 of 0.95 between the red-edge inflection point (REIP) and NNI. However, passive canopy sensors are constrained by time of day and cloud cover.

Recent advances in remote sensing have led to the development of ground-based active optical sensors for applications in precision crop management. Active optical sensors have modulated light emitting diodes that irradiate a plant canopy and measure a portion of the radiation reflected from the canopy without relying on ambient sunlight as used in passive sensors (Holland et al., 2012). They are, thus, independent of environmental light conditions, eliminating the need for frequent calibrations. The GreenSeeker active canopy sensor (Trimble Navigation Limited, Sunnyvale, California, USA) has been commonly used for in-season site-specific N management (Raun et al., 2002; Li et al., 2009; Shaver et al., 2011; Yao et al., 2012). This sensor has a red and near-infrared (NIR) band and provides two vegetation indices, normalized difference vegetation index (NDVI) and ratio vegetation index (RVI). According to Li et al. (2010a), RVI should be selected when using the GreenSeeker sensor to estimate winter wheat N status across sites, years, and growth stages in North China Plain, while NDVI could be used before biomass reached 3736 kg ha^{-1}, or before N uptake reached 131 kg ha^{-1}, due to measurement saturation effect. Yao et al. (2012) also found that RVI was more suitable than NDVI for estimating rice (*Oryza sativa* L.) yield potential in Northeast China.

Recently, a user configurable active canopy sensor, Crop Circle ACS-470 (Holland Scientific, Inc., Lincoln, NE, USA), became commercially available. It provides six band choices (430–470 nm, 530–570 nm, 630–670 nm, 659–681 nm, 720–740 nm and >760 nm), of which three bands can be used at a time. The combinations of three bands can result in many potential spectral vegetation indices. Some of these indices may perform better than the traditional NDVI and RVI indices for estimating crop N status, especially indices based on green and/or red-edge bands (Daughtry et al., 2000). Gitelson et al. (1996) found that Green NDVI (GNDVI) was much more sensitive to the chlorophyll concentration in a wide range of chlorophyll variations than the red NDVI. Close relationships were also found between crop chlorophyll content and chlorophyll index (CI_G, $R_{NIR}/R_{green} - 1$) and red-edge chlorophyll index (CI_{RE}, $R_{NIR}/R_{red\text{-}edge} - 1$) (Gitelson et al., 2003, 2005). Eitel et al. (2010) found two red edge-based indices, canopy chlorophyll content index (CCCI) and normalized difference red-edge index (NDRE) obtained with Crop Circle ACS 470 performed better than NDVI in estimating plant chlorophyll concentration in nurseries. Shiratsuchi et al. (2011) found that two red-edge based three band indices, DATT index ($(R_{760}–R_{720})/(R_{760}–R_{670})$) and MERIS terrestrial chlorophyll index (MTCI, $(R_{760}–R_{720})/(R_{720}–R_{670})$) obtained with Crop Circle ACS 470 sensor, performed best for differentiating maize (*Zea mays* L.) N status under different N and water supply conditions. Recently, Cao et al. (2013) systematically evaluated 43 vegetation indices calculated from three Crop Circle ACS 470 bands (G, RE and NIR) for estimating rice N status. They found that the modified chlorophyll absorption reflectance index 1 (MCARI1) had consistent correlations with rice biomass and PNU (R^2 = 0.79–0.83) across site-years, varieties and growth stages. Four red edge-based indices performed equally well for estimating rice NNI (R^2 = 0.76).

Based on the above literature review, it is hypothesized that the Crop Circle ACS-470 sensor using green, red edge and NIR bands has the potential to improve estimation of crop N status compared with two fixed band active sensors, like GreenSeeker. Some previous studies have compared GreenSeeker and Crop Circle ACS-210 (Holland Scientific, Inc., Lincoln, NE, USA) and found them perform similarly (Shaver et al., 2010, 2011). However, Crop Circle ACS 210 was an older version of the sensor and is also a two fixed waveband sensor using amber (590 nm) and NIR bands. No studies have been reported to compare GreenSeeker with the three band Crop Circle ACS-470 sensor for estimating crop N status. Therefore, the objectives of this study were to: (1) identify important vegetation indices obtained from Crop Circle ACS-470 sensor for estimating plant N status of winter wheat; and (2) evaluate their potential improvements over GreenSeeker NDVI and RVI.

2. Materials and methods

2.1. Study site and experiment design

Several N rate and crop variety experiments were conducted from 2009 to 2012 on winter wheat crops at the Quzhou Experiment Station, China Agricultural University (QZ, 115.0°E, 36.5°N, 37 m above sea level), located in Quzhou County, Hebei Province. The rainfall distribution and mean temperature at the experimental site from 2009 to 2012 is shown in Fig. 1. Experiments 1–3 (Table 1) were used to identify important vegetation indices obtained with Crop Circle ACS 470 sensor for estimating N status indicators. Experiments 4–6 (Table 1) were used to validate the identified indices and established relationships.

Experiment 1 was conducted in 2009–2010. It had five N treatments, including 0 kg ha^{-1} N as a control (CK), optimal N rate (ONR) based on in-season root-zone N management, farmer's N practice (FNP), and 70% and 130% of ONR. In this study, the ONR was set at 137.5 kg N ha^{-1}. The FNP was 300 kg N ha^{-1} (150 kg N