ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2016) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Remote estimation of canopy nitrogen content in winter wheat using airborne hyperspectral reflectance measurements

Xianfeng Zhou [a,b], Wenjiang Huang [a,*], Weiping Kong [a], Huichun Ye [a], Juhua Luo [c], Pengfei Chen [d]

[a] *Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Science, Beijing 100094, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*
[c] *Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China*
[d] *State Key Laboratory of Resources and Environment Information System, Institute of Geographic Science and Natural Resources Research of Chinese Academy of Science, Beijing 100101, China*

Received 17 September 2015; received in revised form 25 June 2016; accepted 27 June 2016

Abstract

Timely and accurate assessment of canopy nitrogen content (CNC) provides valuable insight into rapid and real-time nitrogen status monitoring in crops. A semi-empirical approach based on spectral index was extensively used for nitrogen content estimation. However, in many cases, due to specific vegetation types or local conditions, the applicability and robustness of established spectral indices for nitrogen retrieval were limited. The objective of this study was to investigate the optimal spectral index for winter wheat (*Triticum aestivum* L.) CNC estimation using Pushbroom Hyperspectral Imager (PHI) airborne hyperspectral data. Data collected from two different field experiments that were conducted during the major growth stages of winter wheat in 2002 and 2003 were used. Our results showed that a significant linear relationship existed between nitrogen and chlorophyll content at the canopy level, and it was not affected by cultivars, growing conditions and nutritional status of winter wheat. Nevertheless, it varied with growth stages. Periods around heading stage mainly worsened the relationship and CNC estimation, and CNC assessment for growth stages before and after heading could improve CNC retrieval accuracy to some extent. CNC assessment with PHI airborne hyperspectra suggested that spectral indices based on red-edge band including narrowband and broadband $CI_{red\text{-}edge}$, NDVI-like and ND_{705} showed convincing results in CNC retrieval. NDVI-like and ND_{705} were sensitive to detect CNC changes less than 5 g/m^2, narrowband and broadband $CI_{red\text{-}edge}$ were sensitive to a wide range of CNC variations. Further evaluation of CNC retrieval using field measured hyperspectra indicated that NDVI-like was robust and exhibited the highest accuracy in CNC assessment, and spectral indices ($CI_{red\text{-}edge}$ and CI_{green}) that established on narrow or broad bands showed no obvious difference in CNC assessment. Overall, our study suggested that NDVI-like was the optimal indicator for winter wheat CNC retrieval.

Keywords: Airborne hyperspectral; Spectral index; Canopy nitrogen content; Winter wheat

1. Introduction

Nitrogen (N) is the most important element that affects growing conditions and yield of crops (Ladha et al., 2005). A sufficient supply of nitrogen is crucial to the biochemistry of plants (Clevers and Kooistra, 2012): nitrogen deficiency significantly diminishes the photosynthetic yield of

* Co-first and corresponding author. Fax: +86 10 8217 8177.
E-mail addresses: zhouxf@radi.ac.cn (X. Zhou), huangwj@radi.ac.cn (W. Huang), kongwp@radi.ac.cn (W. Kong), yehc@radi.ac.cn (H. Ye), jhluo@niglas.ac.cn (J. Luo), pengfeichen-001@hotmail.com (P. Chen).

http://dx.doi.org/10.1016/j.asr.2016.06.034

Please cite this article in press as: Zhou, X., et al. Remote estimation of canopy nitrogen content in winter wheat using airborne hyperspectral reflectance measurements. Adv. Space Res. (2016), http://dx.doi.org/10.1016/j.asr.2016.06.034

crops (Feng et al., 2014), while excessive application of nitrogen fertilizer can cause environmental pollution (Ferguson et al., 2002; Hatfield et al., 2008; Inoue et al., 2012). Therefore, timely and accurate assessment of nitrogen status is critical in agricultural management so that the efficiency of nitrogen usage can be improved, thus ensuring a high grain yield while minimizing environmental damage (Tian et al., 2011). Traditional laboratory-based techniques are effective for diagnosing nitrogen status and making nitrogen fertilizer recommendations (Wu et al., 2007). However, these techniques are generally tedious, time-consuming and destructive, and thus cannot be repeated many times in order to make a more representative evaluation of canopy nitrogen status in a particular field or in the fields of a given area (Lemaire, 1997).

Remote sensing technologies have proved to be a potential source for estimates of variables related to biophysical, physiological or biochemical characteristics (Hansen and Schjoerring, 2003). Within the visible and near infrared wave range (400 nm–1000 nm), the absorption features of leaf spectral reflectance are mainly dominated by plant pigments and effects of the leaf cell structure. Research has shown that the absorption features in the blue and red spectral regions is strongly correlated with leaf chlorophyll (Chl) content and a close correlation between foliar nitrogen and chlorophyll content has been reported for various crops such as wheat, maize and potatoes, which provides the bridge for leaf nitrogen estimation using spectral features in visible and near infrared wave range (Clevers and Kooistra, 2012; Oppelt and Mauser, 2004; Yoder and Pettigrew-Crosby, 1995). Although the relationship between nitrogen and chlorophyll contents at the canopy level forms the basis for canopy nitrogen content (CNC) assessment, limited attention have been focused on the relationship among published studies on CNC retrieval. Whether this relationship is dependent on species type, phenological stage, growing conditions and nutritional status (Clevers and Kooistra, 2012), and how the relationship affects CNC estimation need to be intensively studied in order for better understanding of CNC retrieval.

With remote sensing techniques, much progress in nitrogen content assessment have been made in agricultural crops (Clevers and Gitelson, 2013; Clevers and Kooistra, 2012; Inoue et al., 2012; Schlemmer et al., 2013). Among these researches, a semi-empirical method based on spectral indices are commonly used for their high computation efficiency and universality. Sims and Gamon (2002) proposed two hyperspectral indices including normalized difference (ND_{705}) and simple ratio (SR_{705}), and found that ND_{705} and SR_{705} were good estimators of chlorophyll and nitrogen content. Work conducted by Clevers and Kooistra (2012) indicated that the red-edge chlorophyll index ($CI_{red\text{-}edge}$) was linearly related to canopy chlorophyll content using PROSAIL simulations, and it was a good and linear estimator of canopy nitrogen content in both grassland and potato cropping systems. Based on the normalized difference vegetation index (NDVI) formula, Darvishzadeh et al. (2011) developed an inspiring NDVI-like index with hyperspectral data, and it showed remarkable performance in crop variables assessment, such as LAI. Its capability and applicability in other variables retrieval, such as nitrogen and chlorophyll, deserves investigation. To acquire information on agronomic variables at regional scale, the capability of spectral index method in retrieval of crop chlorophyll and nitrogen using multispectral satellite data has been investigated. Clevers and Gitelson (2013) found that the $CI_{red\text{-}edge}$, the green chlorophyll index (CI_{green}), and the MERIS terrestrial chlorophyll index (MTCI) were accurate and linear estimators of canopy chlorophyll and nitrogen contents by focusing on the potential of Sentinel-2 and Sentinel-3 satellites for crop parameters retrieval. Schlemmer et al. (2013) suggested that canopy chlorophyll and nitrogen content in maize could be accurately retrieved using CI_{green} and $CI_{red\text{-}edge}$ based on near infrared, green and red-edge spectral bands of Sentinel-2 satellite. The above mentioned spectral indices established on hyperspectral (narrow) or multispectral (broad) bands indeed exhibited good performance in crop nitrogen and chlorophyll retrieval. Nevertheless, their universality and robustness, and whether these spectral indices established on broad or narrow bands affect their capability in CNC estimation need to be clear.

The development of airborne hyperspectral techniques offers valuable opportunities for agronomic variables retrieval. Airborne hyperspectral sensors could obtain abundant information related to canopy characteristics using numerous fine narrow bands within specific spectrum at regional scale, thus making it possible for rapid and real-time detection of crop variables. The aforementioned spectral indices have been proved to be good estimators for chlorophyll or nitrogen content assessment using field measured hyperspectral or satellite multispectral data. Nevertheless, their applicability in CNC assessment using airborne hyperspectral reflectance measurements is rarely reported. Comprehensive evaluation of these spectral indices in CNC retrieval based on airborne hyperspectral techniques could help to enhance the universality and robustness of these indices. Also, it could contribute to diagnosing nitrogen status in crops and provide basis for satellite remote sensing applications in agricultural production.

Therefore, the aim of the present study was to assess the estimation of CNC in winter wheat using spectral indices derived from airborne hyperspectral measurements. The specific objectives were to: (i) investigate the relationship between CNC and canopy chlorophyll content (CCC) and its influence on CNC estimation using multiple datasets obtained from field experiments conducted under different growing conditions and plant nutritional status; (ii) evaluate the predictive power of broadband and narrowband indices derived from airborne hyperspectral reflectance, that is, ND_{705}, SR_{705}, MTCI, NDVI-like narrowband $CI_{red\text{-}edge}$ and CI_{green}, and broadband $CI_{red\text{-}edge}$ and CI_{green} in winter wheat CNC retrieval. It