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Variations in crop variables within wheat canopies and responses of canopy spectral characteristics and derived vegetation indices to different vertical leaf layers and spikes

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A B S T R A C T

The fundamental basis for applying remote sensing methods to crop assessments is the interrelationships between crop features and canopy spectral characteristics. Thus, a thorough understanding of the differences in the distributions of crop variables among different vertical layers and modules, as well as the effects of these layers and modules on canopy spectral characteristics and derived vegetation indices, is vital to improving the performance of crop monitoring by remote sensing. The main goal of this work was to provide insight into the above issues based on field measurements of winter wheat under different treatments during anthesis. The results demonstrated that the leaf area index (LAI), leaf chlorophyll a and b content (Chl_{a+b}), nitrogen (N) content per unit leaf area (N_L), N concentration on a mass basis (N_M), dry matter accumulation (DM), N accumulation (NA), and water content (W_c) in leaves and stems generally exhibited great vertical differences within wheat canopies during anthesis. There were also significant differences in N_M, DM, NA, and W_c among the different plant modules (i.e., leaves, stems, and spikes) and the entire canopy. Moreover, the removal of wheat spikes and different vertical leaf layers had evident effects on the canopy spectral reflectance, and there were differences in the types and degrees of these effects at different wavelengths and treatments. In most cases, the vegetation indices decreased after removing wheat spikes and different leaf layers, although a few indices increased. There were also some vegetation indices that responded weakly to removal events. In comparison, the vegetation indices mostly showed stronger responses to the removal of the top 1st leaves than the spikes. To a certain extent, the responses to the removal of the top 2nd leaves were comparable to those of the top 1st leaves. The responses of most vegetation indices to the top 3rd leaves' removal were less than the responses to the top 2nd leaves' removal. In the case of the removal of the top 4th leaves and below, many of the R_V (i.e., relative variation rate) absolute values of vegetation indices were greater than those of the top 3rd leaves' removal but smaller than or close to those of the top 2nd leaves' removal; this may partly be because all the withered and dead leaves covering the soil surface were also removed in this case. The above findings indicated that crop features may not be well characterized when they are based solely on leaves, especially only the upper leaves, as the lower leaves, stems, and spikes also have important effects. Moreover, wheat spikes, not just leaves, and even bottom-layer leaves, could have evident effects on canopy reflectance characteristics and derived vegetation indices. More effort is needed in future research to obtain a thorough understanding of the effects of canopy heterogeneity on canopy spectral characteristics and the relationships between crop variables and spectral vegetation indices.

1. Introduction

Dynamic monitoring of crop growth and nutrition status during the growth season is important for precision agriculture, which provides an opportunity to adjust and optimize farm management strategies and to improve and forecast crop yield and quality (Hansen & Schjoerring, 2003; Zhu et al., 2006; Gianquinto et al., 2011; Ryu, Suguri, & Umeda, 2011; Wang et al., 2012). Crop measurements based on destructive point sampling and laboratory methods, despite being effective, are laborious and time-consuming, and thus fail to quickly acquire crop information both temporally and spatially at farm and regional scales (Errecart, Agnusdei, Lattanzi, & Marino, 2012; Li et al., 2012; Zhao, Wang, Wang, & Huang, 2012). The remote sensing technique, which enables timely and nondestructive crop status assessments, is widely used and becoming increasingly important in large-area estimations of crop biophysical, physiological, and biochemical variables, such as the leaf area index (LAI, m^2 leaf/m^2 soil), above-ground biomass (AGB, g/m^2

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soil), leaf chlorophyll a and b content (Chl_{a+b}, mg/g), nitrogen (N) concentration on a mass basis (N_M, %), specific leaf weight (SLW, g/m^2 leaf), N content per unit leaf area (i.e., specific leaf nitrogen, N_L, g N/m^2 leaf), total plant N uptake (N_T, g N/m^2 soil), tiller density (TN, number/m^2), grain yield (GY, g/m^2 soil) and protein content (GPC, mg/g), photosynthetic light use efficiency (PLUE, mol CO_2/mol photons), radiation use efficiency (RUE, g/MJ), harvest index (HI, unit-less), leaf water content (LWC, g/cm^2 leaf or g/g), canopy water content (CWC, g/m^2 soil), stem water soluble carbohydrates (WSC, mg/g or g/m^2 soil), etc. (Filella, Amaro, Araus, & Penuelas, 1996; Broge & Mortensen, 2002; Scotford & Miller, 2004; Xue, Cao, & Yang, 2007; Clevers, Kooistra, & Schaepman, 2010; Fitzgerald, Rodriguez, & O'Leary, 2010; Yao, Zhu, Tian, Feng, & Cao, 2010; Li, Luo, & Ma, 2011; Li, Luo, Xue, et al., 2011; Zhang et al., 2012; Zhao et al., 2012; Delegido et al., 2013; Ecarnot, Compan, & Roumet, 2013; Wang, Hunt, Qu, Hao, & Daughtry, 2013; Dreccer, Barnes, & Meder, 2014; Feng et al., 2014).

The fundamental basis for applying quantitative remote sensing methods in agricultural surveys is the interrelationships between crop features and canopy spectral characteristics at visible, near-infrared, and middle-infrared wavelengths (Hoffer, 1978). Besides soil background, sun-target-view geometry, atmospheric state, etc., canopy structure and biochemical composition are the main factors controlling canopy reflectance spectra (Wang & Li, 2013). As in the above-mentioned literatures, crop variables are generally estimated using the canopy reflectance within their respective sensitive wavelengths or the vegetation indices derived from them. However, crop canopies generally have a three-dimensional structure, and many variables within (e.g., leaf N, stem N, leaf chlorophyll, leaf area, leaf photosynthetic rate, leaf water content, dry matter) vary considerably among different spatial positions (Tian, Cao, Wang, & Zhu, 2004; Wang et al., 2005; Ciganda, Gitelson, & Schepers, 2008; Li et al., 2009; Shi et al., 2009; Li, Tang, Zhang, Cao, & Zhu, 2011; Bertheloot, Andrieu, & Martre, 2012; Winterhalter, Mistele, & Schmidhalter, 2012). Though canopy spectral reflectance contains the contributions of all the leaves within a canopy, the contributions of the different canopy layers are expected to be very different (Xiao et al., 2008; Wang & Li, 2013). Moreover, other than leaves, other crop modules (i.e., spikes and stems) would also have large effects on canopy reflectance spectra, which have seldom been investigated. Consequently, in addition to a full understanding of canopy spectral characteristics, a thorough knowledge of the effects of crop modules in different spatial positions on the overall canopy spectral characteristics and derived vegetation indices is critical for the proper and effective use of hyperspectral remote sensing data for crop monitoring.

The purpose of the present study was to provide insight into the above issue. Winter wheat (*Triticum aestivum* L.), a primary food source for many people in China and the world, was used in this research. We first investigated the differences in LAI, Chl_{a+b}, leaf and stem N content, water content, and dry matter (DM, g/m^2 soil) and N accumulation (NA, g N/m^2 soil) amount among different vertical layers, as well as the differences in N content, water content, DM, and NA among different crop modules (leaves, stems, and spikes) and the entire canopy. Then, the responses and sensitivity of canopy spectral reflectance and the derived vegetation indices to the removal of wheat spikes and different vertical leaf layers were analyzed. Finally, we proposed that more attention should be given to canopy vertical heterogeneity in crop assessments made with remote sensing to improve the effectiveness and accuracy and discussed the specific issues that should be addressed and related approaches that may be used in future research.

2. Materials and methods

2.1. Field experiments

The study was conducted at the National Experimental Station for Precision Agriculture (116.44° E, 40.18° N), located in the northeast area of Beijing, China, which has a sub-humid continental monsoon climate. The annual mean temperature is 13 °C, and the average annual rainfall is 508 mm. The soil is mainly silt clay with an organic content of 1.8%. Winter wheat is commonly sown in late September with a row spacing of 0.15 m and harvested in mid-June of the next year.

The field data used in this study was collected during the anthesis stage of the 2012/2013 wheat season. Single-factor field experiments using the following treatments were conducted: three wheat cultivars with different geometry types (spread, semi-spread, and erect), three different N fertilization levels (0, 225, and 350 kg N/ha), and two different sowing rates (165 and 82.5 kg seeds/ha). For the three different N fertilization level treatments, the same wheat type (semi-spread) and sowing rate (165 kg seeds/ha) were used. The N fertilizer amount of each level was divided into halves and applied at sowing as basal-dressing and at jointing as top-dressing. For the three different wheat type treatments, the same N fertilization amount and sowing rate were used, which were 225 kg N/ha and 165 kg seeds/ha, respectively. For the two different sowing rate treatments, the same wheat type (semi-spread) and N fertilization rate (225 kg N/ha) were used. Hence, a total of six treatments were set up (Table 1), as the treatment with the semi-spread wheat type, normal N fertilization amount (225 kg N/ha), and normal sowing rate (165 kg seeds/ha) was common to all the treatment categories. Each treatment had four replicas, three for destructive samplings to determine the crop variables of the different vertical layers and modules, and one for the spectral reflectance measurements of the entire canopy and those canopies with wheat spikes or different vertical leaf layers removed. Thus, a total of twenty-four plots, each with an area of 10.8 × 19 m, were used. For all the plots, common strategies for irrigation and disease, insect, and pest control were used to meet the needs for crop growth.

2.2. Crop variables measurements

The various crop biophysical and biochemical variables of the different vertical layers and plant modules were determined by field sampling and laboratory analyses. Before sampling, crop population density information was collected by investigating the number of wheat stalks within a sample square of 0.6 × 0.6 m in each plot. Then, three crop samples, each containing 50 wheat stalks, were taken randomly from three replicate plots of each treatment and immediately brought back to the laboratory. The plant samples were kept upright as the natural state after removing their roots and were clipped into four equal layers. Actually, in the study period of anthesis of winter wheat, the four equal vertical layers beginning from the base of the plants generally contained the top 4th leaves and below, the top 3rd leaves, the top 2nd leaves, the top 1st leaves, respectively. The top layer was divided into leaves, stems (including sheaths), and spikes, and the other three layers were separated into leaves and stems. For each layer, the leaves were further separated into the green and yellow parts.

For each layer, the green leaf area was measured with a portable laser leaf area meter (CI-203, CID, USA). The chlorophyll content (Chl_{a+b}, mg/g) of the green leaves was determined by a standard method in the laboratory, that is, it was extracted with 95% ethanol and then measured with a UV–visible spectrophotometer. The fresh weights of each category as described above (i.e., spikes, stems, green and yellow parts of leaves) were also determined, and then oven-dried at 70 °C for 72 h to obtain their dry weights. Subsequently, the dried materials were ground and the nitrogen concentrations (N_M, %) of each category were determined using the Kjeldahl technique. Based on the above measurement procedures and the recorded information, all the crop variables, including the LAI, Chl_{a+b}, and N_L of the green leaves, and the N_M, DM, NA, and water content (W_c, %, on a fresh weight basis) of the different crop modules in the different vertical layers and the entire canopy, were acquired by direct measurements or indirect calculations.