Diagnostic Assessments of Plant Condition Using Multiangular Remote Sensing Measurements and BRDF Models

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Abstract Plant condition assessment using remote sensing techniques have been associated with spectral vegetation indices such as the normalized difference vegetation index (NDVI). A change in NDVI values has been normally regarded as changes in vegetation amount or density. The spectral properties of plants, which are directly related to the health conditions, would also result in changes in spectral vegetation indices. Consequently, a lower vegetation index value may result from either lower density or nutrient stress, or a combination of the two. This would limit the use of vegetation indices as a monitoring tool. Bidirectional reflectance distribution function (BRDF) models treat plant density and optical properties differently and, therefore, can help to assess plant condition objectively. In this study, multiangular spectral reflectances were measured over two winter wheat canopies: one being under nitrogen stress and the other not. These multiangular measurements were then used in inversions of BRDF models to estimate the optical properties and the plant densities. The results show that it is feasible to obtain simultaneously the optical properties and plant densities and, therefore, it is possible to use BRDF models and multiangular remote sensing measurements to make diagnostic analysis of nitrogen—related plant conditions. The results also revealed some limitations of this approach such as inversion problems and computation time.

Key words BRDF, Inversion, NDVI, Diagnostic assessments of plant condition

1 INTRODUCTION

Monitoring vegetation and mapping its spatial distribution via remote sensing techniques have been associated with computations of vegetation indices such as the normalized difference vegetation index NDVI:

$$NDVI = (\rho_{NIR} - \rho_{red})/(\rho_{NIR} + \rho_{red}) \qquad (1)$$

where ρ is reflectances in the near infrared (NIR) and red spectral region. The rationale is based on the distinctive reflectances properties of vegetation compared with the background substrates. While soils tend to have a flat spectrum (Fig. 1), vegetation has substantially high reflectances in the NIR, but very low in the red spectral region. To distinguish vegetation from its background soils, the difference ($\rho_{NIR} - \rho_{red}$) or the ratio (ρ_{NIR}/ρ_{red}) thus has been used in various equations of vegetation indices. Changes in vegetation

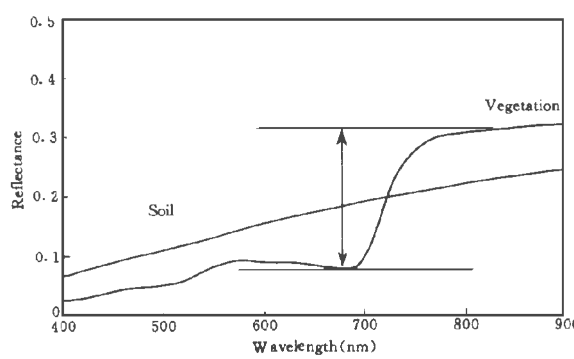

Fig. 1 Spectral signature of soils and vegetation

indices have been traditionally regarded as a consequence of changes in the vegetation amount or density and, therefore, vegetation indices have been extensively used in the estimation of vegetation amount such as leaf area index and biomass productions.

The major processes responsible reflective spectral properties are the scattering and absorption by the vegetation, which are in turn controlled by the chlorophyll contents and pigmentation. Because of their special structures of these chemical elements, vegetation appears to be transparent for NIR, but opaque for red light. Changes in chlorophyll contents, due to nutrient deficiencies and environmental stresses such as water shortage or maturity, will consequently result in changes in spectral properties of its reflectances. Therefore, either reduction in total vegetation amount or vegetation stresses can result in decreases in vegetation indices. In other words, the decreases in vegetation indices can be resulted from either low vegetation density or environmental stress, or the mixture of the two. In this case, the use of vegetation indices can be limited, and interpretation of vegetation conditions may be uncertain.

This ambiguity may be resolved using multiangular measurements and bidirectional reflectance distribution function (BRDF) models. Unlike in most vegetation index equations, the optical properties of vegetation and its density are parameterized separately in some of the physically based models. Inversion of these models with multiangular remote sensing measurements may thus provide information not only about the density, but also the optical properties. The objective of this study is to explore the use of BRDF models and multiangular remote sensing measurements for diagnostic assessment of vegetation conditions, with respect to plant density and nutrient deficiency stresses.

2 APPROACH

Two BRDF models were used for estimation of optical properties and pant densities. The first one is a physically based model by Verstraete *et al.*[1]:

$$\rho(\theta_s, \theta_v, \varphi) = \frac{\omega}{4}\frac{k_s}{k_s\cos\theta_s + k_v\cos\theta_v}\left[(1 + P_v(G)) \cdot P(\xi) + \left(H\frac{\cos\theta_s}{k_s}H\left(\frac{\cos\theta_v}{k_v}\right) - 1\right)\right] \quad (2)$$

where

$$P_v(G) = \frac{1}{1 + V_p(G)}$$

$$P(\xi) = \frac{1 - \Theta^2}{[1 + \Theta^2 - 2\Theta\cos(\pi - \xi)]^{3/2}}$$

$$V_p(G) = 4\left(1 - \frac{4}{3P}\right)\frac{G}{2rL}\frac{\cos q_v}{k_v}$$

$$H(x) = \frac{1 + x}{1 + (1 - \omega)x}$$

$$G = \sqrt{\tan^2\theta_s + \tan^2\theta_v - 2\tan\theta_s\tan\theta_v\cos\varphi}$$

$$\kappa_x = \Psi_1 + \Psi_2\cos\theta_x$$

$$\Psi_1 = 0.5 - 0.6333\chi_1 - 0.33\chi_1^2$$

$$\Psi_2 = 0.877(1 - 2\Psi_1)$$

$$\cos\xi = \cos\theta_s\cos\theta_v + \sin\theta_s\sin\theta_v\cos\varphi$$

The parameters ω and Θ are single scattering albedo and phase function parameters. These two parameters can be integrated to obtain leaf optical properties[2], provided that the leaf angle distribution is quasi-uniform and the asymmetry parameter is close to zero. Therefore, by inversion of this model, leaf optical properties (leaf reflectance $\rho\lambda L$, transmittance $\tau\lambda L$), can thus be inferred with solely multiangular remote sensing measurements.

The leaf optical properties are also parameters used in the SAIL model[3] which involves a set of radiative transfer equation as proposed by Suits[4]:

$$dE_S/dx = kE_S \quad (3a)$$

$$dE_-/dx = -sE_s + aE_- - \sigma E_+ \quad (3b)$$

$$dE_+/dx = sE_S + \sigma E_- - aE_+ \quad (3c)$$

$$dE_0/dx = wE_S + vE_- + uE_+ - KE_0 \quad (3d)$$

where E_S is direct solar flux, E_- and E_+ are diffuse downward and upward flux, E_0 is total solar irradiance, K is extinction coefficient, and k, s, s', a, σ are coefficients defined by Bunnik's[5]. In the SAIL model, Verhoef[3] characterized vegetation by a leaf inclination distribution function (LIDF), leaf reflectance ($\rho\lambda L$), transmittance ($\tau\lambda L$), and leaf area index (LAI), and a soil substrate by its reflectance P_s. With these vegetation parameters he derived k, s, s', a, σ coefficients and predicted bidirectional reflectance as a function of angular parameters of the sun and sensors. Because this model requires an LAI parameter as input, inversion of this model allows one to obtain LAI values[6-8].

By inverting these two models, one can obtain not only the plant density parameters (LAI), but also the leaf optical properties. The criterion for inversion processes was to optimize the following merit function δ^2:

$$\delta^2 = \sum\left(\rho_k - \rho_m(\theta_s, \theta_v, \varphi, p)\right)^2 \qquad (3)$$

where ρ_k is the measured while ρ_m the model predicted values. This function was optimized to find the best set of parameters P using the simplex algorithm[9].

3 EXPERIMENT

A Free—Air CO_2 Enrichment experiment was conducted from December of 1995 to May 1996 at the Maricopa Agricultural Center near Phoenix, Arizona, as a continued effort to investigate the carbon dioxide (CO_2) effects on agricultural crops and environment. The major objective was to investigate the effects of elevated CO_2 concentration on plant physiology and yield production. Another objective was to investigate the spectral properties of winter wheat of same variety under different nitrogen (N) treatments.

Winter wheat was planted in earlier December of 1995 in two fields of the same soil type. Throughout the following growing season, one field was furnished with plenty of nitrogen (350kg/ha) whereas the other one was under stressed (70kg/ha), allowing investigations of nutrient stress detection with remote sensing technique. Both fields were treated with the same frequency irrigation. Plant samples were collected at a weekly interval to measure the chlorophyll, pigment, nitrogen contents, and leaf area index by destructively taking samples.

Ground based multiangular spectral measurements with a radiometer equipped with 4 spectral bands, corresponding to blue, green, red, and NIR spectral region. The radiometer was mounted on an apparatus 2 meters above the ground, along with an angle measuring device to record the sensor viewing angles. The scanning directions were in principle plane (pp), 45 and 90 off the pp, and 110 degrees of the true north, the last one corresponding to the scanning direction of the SPOT satellite. The BRF measurements (Fig. 2) were made twice during the entire growing season (Feb. 15 and April 27, corresponding to day of year, DOY, of 46 and 114) in both low and high nitrogen treatment fields. High spectral reflectances of both of the wheat canopy and individual leaves were measured on a weekly basis to obtain leaf optical properties.

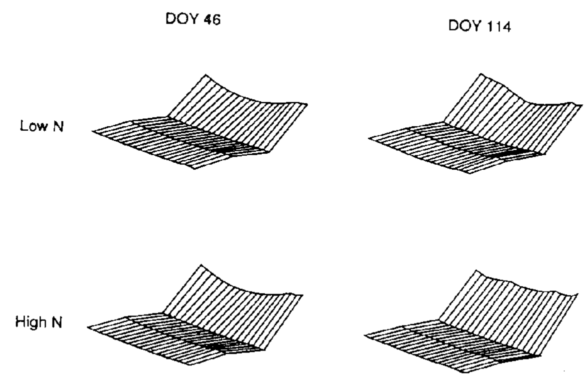

Fig. 2 Spectral properties of the two wheat canopies treated with low and high nitrogen applications on DOYs of 46 and 114, 1996

4 RESULTS

Data in Fig. 3 indicate that the low N treatment

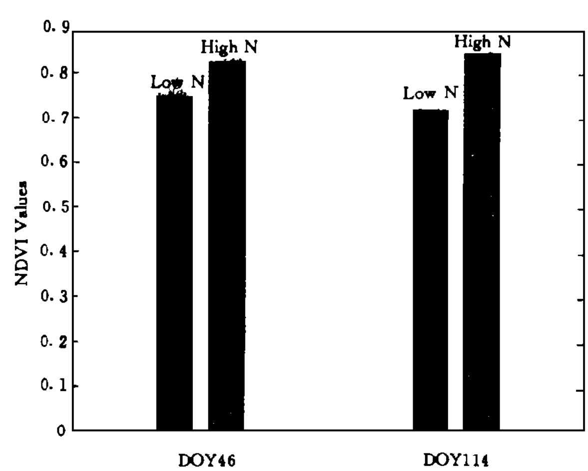

Fig. 3 Measured NDVI values of the two wheat canopies treated with low and high nitrogen applications on DOYs 46 and 114

resulted in consistent lower NDVI values than the high N treatment. The lower values of NDVI could possibly result from lower plant density in this field because of insufficient N applications, or due to lower concentration of chlorophyll and pigment, or due to both. In fact, the field measurements indicated that both of chlorophyll (Fig. 4) and leaf area index (Fig. 5) were lower in the N stressed plants than the non—stressed plants.

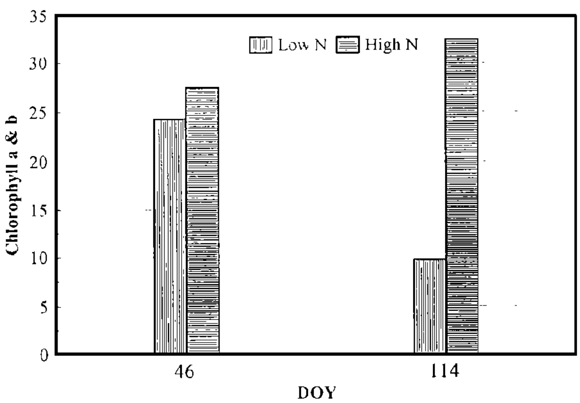

Fig. 4 Measured chlorophyll contents of wheat canopies of both high and low nitrogen treatments

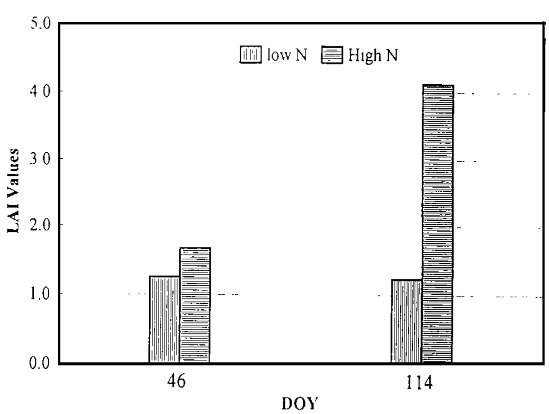

Fig. 5 Measured leaf area index (LAI) of wheat canopies of both high and low nitrogen treatments

Insufficient N applications not only limited the plant growth (fewer leaves were produced), but also altered the chemical concentrations of the plants (lower chlorophyll and pigment concentrations), both of which contributed to the reduction in the spectral vegetation indices. Through an inversion of the two BRDF models, these combined effects were separated. In Fig. 6, the estimated leaf optical properties of low and high N treatments are compared. In the early growing stage (DOY 46), the

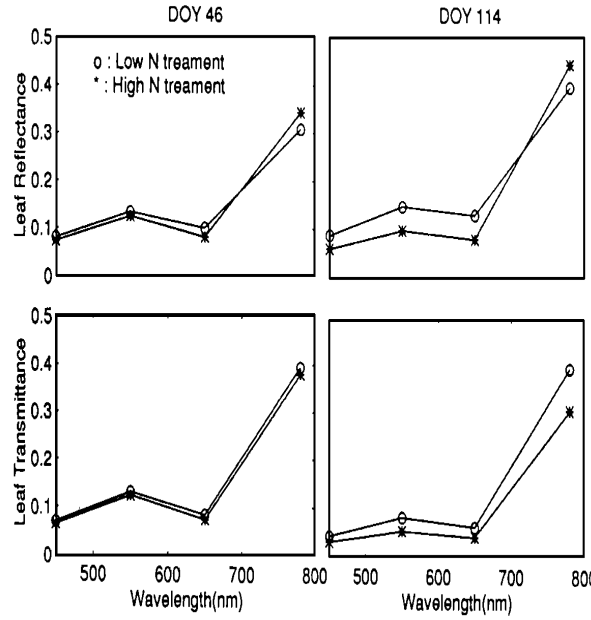

Fig. 6 Estimated leaf optical properties wheat canopies of both high and low nitrogen treatments

stressed plants had high leaf reflectances in all visible regions (blue, green, red). The leaf transmittance of the stressed plants was close to the non—stressed plants.

These differences may not be significant, but indicated the stress. Due to low reflectances in the NIR region, the calculated vegetation indices will be decreased. At this time, the N deficiencies between the two treatments were not significant, partly because the soils contained a plenty of N from previous year residues. As growth proceeded, the N—induced deficiencies (DOY 114) become more pronounced. The low leaf reflectances in the NIR region caused decreases in LAI estimations. The leaf reflectances in the visible region were substantially higher for the N stressed treatment, indicating that the plants had nutrient deficiency. Field notes also indicated that the N stressed plants appear yellow in color (leaf reflectances in red are higher for stressed plants than that of healthy plants). The estimated LAI values were compared in Fig. 7. Although it appeared that the LAI values for the early date (DOY 46) were overestimated, the estimated values agreed well with field measurements.

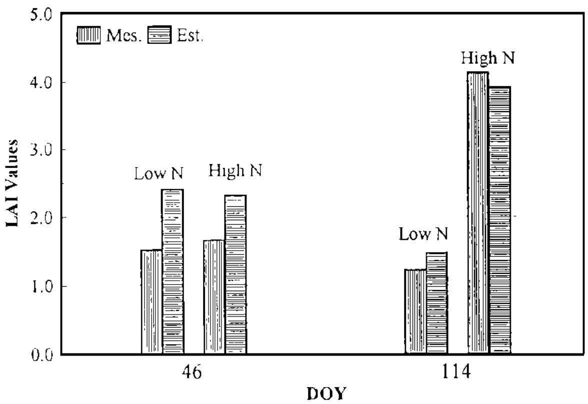

Fig. 7 Comparison between the estimated and measured values of leaf area index

5 CONCLUDING REMARKS

The proposed use of multidirectional remote sensing measurements and BRDF models enabled retrievals of both plant density and optical properties, the latter being directly related to the plant environmental stress such as nitrogen deficiencies. Use of BRDF models and remotely sensed multiangular data would thus allow farmers and natural resources managers to map not only the spatial densities, but also optical properties, providing a diagnostic tool for crop growth monitoring. Operational strategies should be developed to use daily multiangular observations and BRDF models for resources management.

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用多角度遥感观测和 BRDF 模型对植物状况诊断评估

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摘 要 用遥感技术进行植物评估可与光谱植被指数联系起来，如规一化差分植被指数 NDVI。NDVI 值的变化一般被认为是植被数量和密度的变化，但直接与植物生长状况有关的植物光谱特性也会导致光谱植被指数的变化。因此，低植被指数可能由于低密度或肥料不足二者之一或共同造成。这会限制植被指数作为监测手段的使用。二向反射分布函数 BRDF 模型把植物密度和光学特性区别对待，因而它有助于植物状况的客观评估。在这项研究中，我们测量了两个冬小麦冠层多角度光谱反射：一个氮肥充足，一个贫乏。这些测量随后用于 BRDF 的反演，来估计光学特性和植物密度。结果表明，同时获得这两种参数是可行的。因此，用 BRDF 和多角度遥感测量手段进行氮肥养料有关的植物状况诊断分析是可能的。结果也显示出这种方法中如反演和计算时间所带来的一些局限性。

关键词 BRDF，反演，NDVI，植物状况诊断