

ANALYSIS ON OPTIMAL BANDS FOR RETRIEVAL OF MIXED CANOPY CHLOROPHYLL CONTENT BASED ON REMOTE SENSING

GAO Yan-hua^{a,b,*}, CHEN Liang-fu^{a,c}, ZHOU Xu^d, LI Li^a, LIU Qin-huo^a, TIAN Guo-liang^a

^a State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing Applications, Chinese Academy of Sciences, Beijing 100101, China

^b Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

^c The Center for National Spaceborne Demonstration, Beijing 100101, China

^d National Geomatics Center of China, Beijing 100044, China

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ABSTRACT:

A large number of spectral indices have been developed for estimation of leaf chlorophyll content. However, in most cases these indices have been tested for only one or at most a few related species and thus it is not clear whether they can be applied across species with varying leaf structure characteristics. The main objective of the study was to find spectral bands that are sensitive to variation in chlorophyll content and are relatively insensitive to species and leaf structure variation, and determine optimal wide bands range for retrieving chlorophyll content of mixed canopies that consist of diverse species, then develop wide bands based approach to retrieve chlorophyll content of mixed canopies. We analyzed the correlation between chlorophyll content and reflectance, the first derivative of reflectance using LOPEX93 database respectively. The results showed: (1) red edge spectral indices provided relatively good correlation with chlorophyll content when applied across a wide range of species; (2) the optimal band for estimation of chlorophyll content was found at 698-715nm range; (3) for the first derivative of reflectance, the optimal bands for estimation of chlorophyll content were at 720-735nm range and 535-550nm range.

1. INTRODUCTION

The content of chlorophyll is an important biomarker of the actual plant status. Natural or anthropogenic stressors have a direct effect on chlorophyll content, which suggests that a chlorophyll measurement may provide information on the plant physiological state. Chlorophyll content is also linked to nitrogen content and, hence, to photosynthesis. Nondestructive remote determination of leaf chlorophyll content permits the measurements of changes in pigments over time for leaves and avoids time-consuming and expensive traditional chlorophyll concentration measurements. A number of studies have been carried out to design an appropriate algorithm to estimate the chlorophyll content of structurally homogeneous agriculture crops (Daughtry et al., 2000; Haboudane et al., 2002), but also for structurally complex coniferous forest canopies (Zarco-Tejada et al., 2004), using optical remote sensing data. Many spectral indices have been developed for estimation of leaf chlorophyll content. However, in most cases these indices have been tested for only one or at most a few related species and thus it is not clear whether they can be applied across species with varying leaf structure characteristics.

The main objective of the study was to find spectral bands that are sensitive to variation in chlorophyll content and are relatively insensitive to species and leaf structure variation, and determine optimal bands range for retrieving chlorophyll content of mixed canopies that consist of diverse species, then develop wide bands based approach to retrieve chlorophyll content of mixed canopies.

2. METHODS

2.1 database used in this study

In order to have a wide range of variation of leaf internal structure, pigmentation, water content and biochemical components, plant species with different types of leaves were required. The LOPEX93 database was used as a good data source. The LOPEX93 experiment was conducted during the summer of 1993 in the Joint Research Center at Ispra, Italy. About 70 leaf samples representative of more than 50 species were collected from trees, crops and plants, and the leaf hemispherical reflectance and transmittance were measured over the 400nm–2500nm wavelength interval. In parallel with the spectral measurements, many physical and biological measurements were performed on the samples (Hosgood et al., 1994), such as chlorophyll content, water content and carotenoids content. In this database, 62 fresh leaf samples with measurement of spectral reflectance and chlorophyll content were available.

2.2 Data Analysis

This study focused on developing an understanding of the relationship between the spectral reflectance properties of diverse vegetation and the content of chlorophyll within the constituent plant tissue. Correlation analysis was performed to determine the strength of relationships between total chlorophyll content and spectral reflectance, the first derivative of reflectance respectively based on LOPEX93 database.

* GAO Yan-hua*, A 11 Datun Road, Chaoyang District, Beijing, 100101 China (E-mail: gaoyh@igsnrr.ac.cn)

Correlation analysis between chlorophyll content and spectral reflectance

Towards exploring the bands range which could have high significant correlation with chlorophyll content, correlation analysis was carried out in 400-900nm spectral region. Linear and nonlinear correlation analysis was performed respectively to locate the optimal spectral regions (Figure 1 and Figure 2).

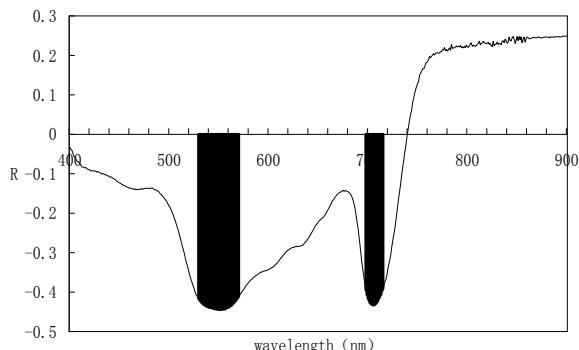


Figure 1. Variation with wavelength (400-900nm) in linear correlation coefficient (R) between reflectance and chlorophyll content

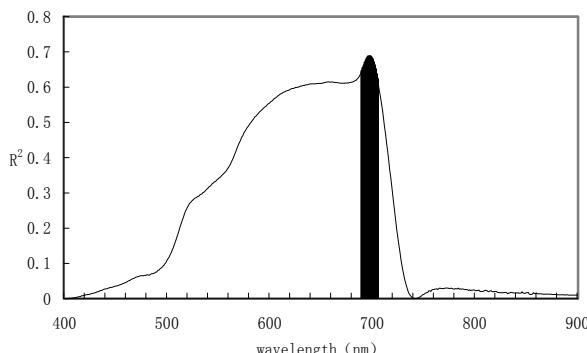


Figure 2. Variation with wavelength in the coefficient of determination (R^2) obtained when regressing reflectance against chlorophyll content, using an exponential model

The reflectance in 400-500nm region showed the lowest correlation both linear and nonlinear with chlorophyll content. It has been previously shown (e.g., Gitelson et al., 1996a) that the red wavelength reflectance near 670nm is only sensitive to chlorophyll *a* levels below 0.003mg/cm². Such low levels of chlorophyll can only be found in highly stressed or senescing leaves, such as yellow autumn leaves of deciduous species (Datt, 1998). Though the nonlinear correlation between reflectance near 670-680nm and chlorophyll content is higher, due to the strong absorption by chlorophyll, the reflectance at 680nm remained nearly constant with increasing chlorophyll content. So 400-500nm and 670-680nm spectral regions are not the optimal band to estimate chlorophyll content. And the reflectance near 705nm showed highest correlation both linear and nonlinear with mixed leaves chlorophyll content.

Correlation analysis between chlorophyll content and the first derivative of reflectance

The first derivative of the reflectance curves can provide information about rate of change along the curve and at what wavelength these changes occur. Such insight is not apparent with simple reflectance curves. Chlorophyll variations can

induce changes in the first derivatives of the reflectance spectra. The first derivatives of reflectance spectra can be defined as:

$$\Delta R_i = \frac{\rho_{i+1} - \rho_{i-1}}{\Delta\lambda}, \quad (1)$$

where ρ_{i+1} and ρ_{i-1} are the reflectance at wavelength $i+1$ and $i-1$ respectively, $\Delta\lambda$ is the wavelength difference between $i+1$ and $i-1$, so $\Delta\lambda$ is equal to 2 here. According to this equation, the first derivatives of the reflectance of fresh leaves in LOPEX93 database can be calculated.

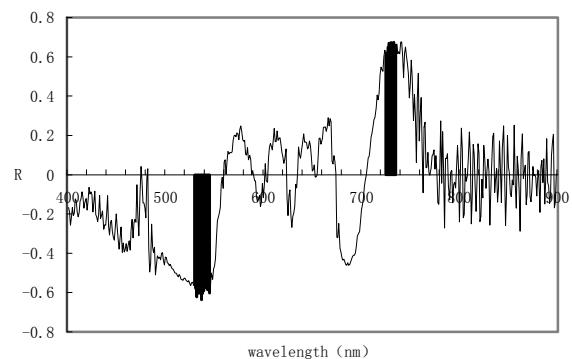


Figure 3. Variations with wavelength in the correlation coefficient obtained when regressing chlorophyll content against δR , using a linear model

Figure 3 illustrated the variations with wavelength in the coefficient for the relationship between the amplitude of the first derivative, δR , and chlorophyll content. The plot was constructed using a linear regression model to derive the R value. The plot showed a good degree correlation in several bands within the 400-800nm region. However, the highest correlation between δR and chlorophyll content was near 530-545nm and 725-735nm.

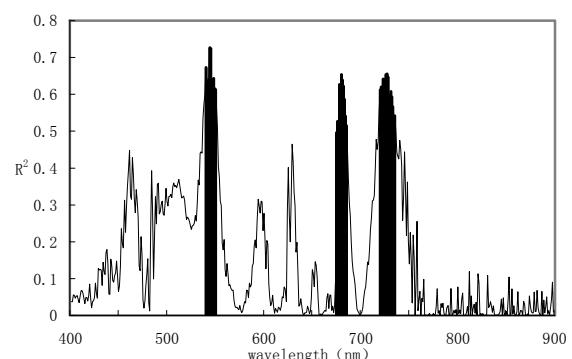


Figure 4. Variations with wavelength in the coefficient of determination (R^2) obtained when regressing δR against chlorophyll content, using an exponential model

Figure 4 illustrated the variations with wavelength in the coefficient of determination for the relationship between the amplitude of the first derivative, δR , and chlorophyll content. The plot was constructed using an exponential regression model to derive the R^2 value, the best fit model for most wavelengths, and shows a good degree correlation in several bands within the

400-800nm region. However, the greatest correlation between δR and chlorophyll content was near 540-550nm、675-685nm and 720-735nm.

2.3 optimal bands range

The criterions to determine the optimal wavelength regions for estimating the mixed canopy chlorophyll content are: (1) the reflectance or the first derivative of reflectance in these wavelength regions should show the higher correlation with chlorophyll content; (2) the optimal wavelength regions should be those regions in which the reflectance or the first derivative of reflectance shows the highest correlation both linear and nonlinear with the mixed leaves chlorophyll content. Due to the nonlinear correlation involving the saturation problem, the stronger linear correlation is dominant criterion. The criterions not only ensure high correlation between reflectance of optimal wavelength regions and chlorophyll content, but also avoid the information saturation problem in relevant bands.

In order to develop better algorithms for estimating chlorophyll content, the wavelength bands with maximum and minimum

sensitivities to chlorophyll content were identified from correlogram plots showing the correlation coefficients between reflectance and chlorophyll content at all wavelength. The determination of optimal bands to indicate the mixed canopy chlorophyll content depended on the integration of linear and nonlinear correlation analysis. The overlap regions with higher linear and nonlinear correlation were determined as optimal bands. Figure1, Figure2, Figure3, and Figure4 provided the information for locating the overlap regions of reflectance or the first derivative of reflectance. In addition, the overlap wavelength regions, in which the reflectance was insensitive to chlorophyll content, can serve as the reference bands.

Band ratios were calculated by dividing the reflectance in a band insensitive to pigment content to the reflectance in bands highly sensitive to pigment content. The 698-710nm band was found to be the best sensitive band for constructing reflectance ratios. Pigment do not absorb NIR radiation, so the NIR bands as the insensitive terms for developing reflectance-based algorithms for estimating leaf pigment content.

	Correlation analysis	Significant correlated spectra region(nm)	Insensitive bands(nm)	Sensitive bands(nm)	Extend bands(nm)	Reference bands(nm)
reflectance spectra	Linear model (R)	698-715 $ R \geq 0.4$ 530-570 $ R \geq 0.42$	740-900	698-710	698-715	740-900
	Nonlinear model (R^2)	581-712 $R^2 \geq 0.5$ and: 621-706 $R^2 > 0.6$	740-900			
the first derivative of reflectance	Linear model (R)	723-742 $R > 0.6$, and: 727-736 $R > 0.65$ 531-545 $R > 0.57$	557-563 670-674 703-708	723-735 539-545	720-745 535-550	703-708 670-674
	Nonlinear model (R^2)	719-735 $R^2 > 0.54$, and: 720-728 $R^2 > 0.6$ 675-685 $R^2 \geq 0.5$, and: 678-682 $R^2 \geq 0.61$ 537-552 $R^2 > 0.5$, and: 539-550 $R^2 > 0.61$	564-587 694-705 656-674			

Table 1. Result of correlation analysis between chlorophyll content and reflectance spectra, the first derivatives of reflectance spectra, respectively

Reflectance in the main chlorophyll absorption region near 680nm has been used for a long time as an indicator of chlorophyll content of leaves. However, the relationship between reflectance near 680nm and chlorophyll content has been shown to become saturated at medium to high chlorophyll contents, and is therefore the least sensitive to variation in chlorophyll content. The reflectance near 680nm was found to be the better reference band than the NIR bands (Datt et al., 1998). In this study, correlation analysis results showed that 740-900nm region is the better reference bands, besides the region near 680nm.

Table 1 showed that the sensitive reflectance regions to chlorophyll content are not the same regions of the sensitive derivative reflectance.

3. RESULTS

The chlorophyll index ($CI = (R_{750}-R_{705})/(R_{750}+R_{705})$), which was proved to be the better indicator of mixed leaves chlorophyll content (Figure 5) using LOPEX93 database. However, CI is narrow band index. According to analysis on the optimal wavelength regions for estimation of mixed canopy chlorophyll content, it is possible to extend CI to be wide band index. To validate the optimal bands in table 1, we defined the CI_{wide} as

$$CI_{wide} = (\int_{750}^{760} R_\lambda d_\lambda - \int_{700}^{710} R_\lambda d_\lambda) / (\int_{750}^{760} R_\lambda d_\lambda + \int_{700}^{710} R_\lambda d_\lambda) \quad (2)$$

Where CI_{wide} is the extended chlorophyll index, R_λ is the reflectance at wavelength λ . The index CI_{wide} described by equation (2) was tested. The strong relationship between chlorophyll content and CI_{wide} is indicated by the scatterplot in Figure 6.

In addition, the reflectance integration of random 10nm interval between 740nm and 900nm can substitute the reflectance integration between 750nm and 760nm in equation (2). In

equation (2), for example, substituting $\int_{840}^{850} R_\lambda d_\lambda$ for $\int_{750}^{760} R_\lambda d_\lambda$, the index kept the high correlation with mixed leaves chlorophyll content ($R^2=0.7991$). So the index is calculated based on the reflectance of wavelength range of 698-710nm and 740-900nm can serve as indicator of mixed canopy chlorophyll content.

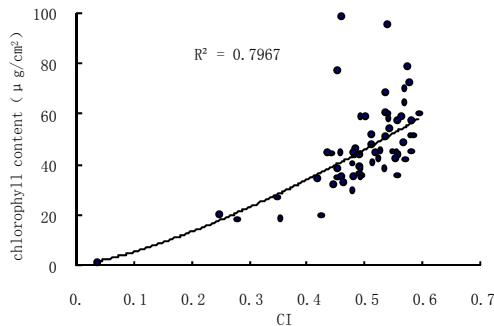


Figure 5. The relationship between chlorophyll content and CI

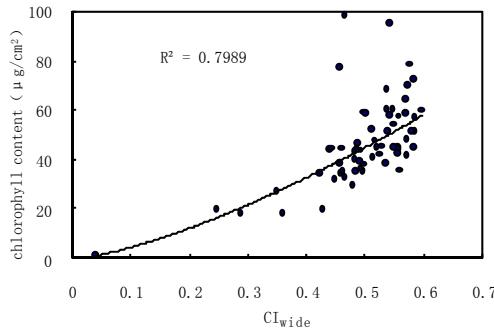


Figure 6. The relationship between chlorophyll content and CI_{wide}

Filella et al. (1995) suggested that wheat canopy chlorophyll *a* concentration had strong linear relationship with the sum of the amplitudes of the first derivative between 680nm and 780nm and the amplitude of the main peak of the first derivative. The area of the derivative under the red edge ($ADR = \int_{680}^{760} D$) also has

been developed to indicate the total chlorophyll content. Based on the LOPEX93 database, we tested ADR for its application to indicate total chlorophyll content of mixed canopy. Figure 7 illustrated that ADR can not be the indicator of the mixed canopy chlorophyll content.

According to the analysis results in the table 1, the amplitudes of the first derivative between 720nm and 745nm can indicate the mixed canopy chlorophyll content. So the algorithm of ADR was modified to narrow the area of the derivative under the red edge to 725-735nm range. The result in Figure 8 showed that the area of the derivative under the red edge between 725 and 735nm was good indicator of the mixed canopy chlorophyll content. The sum of the amplitudes of the first derivative between 535nm and 550nm had strong correlation ($R^2=0.71$) with mixed canopy chlorophyll content (Figure 9).

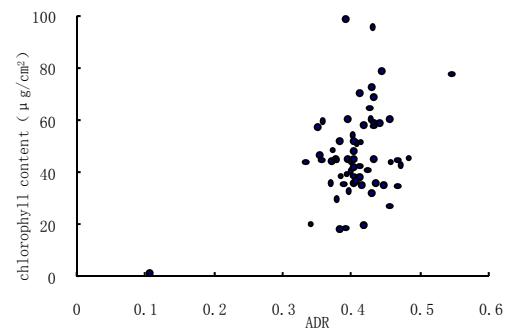


Figure 7. the relationship between chlorophyll content and ADR

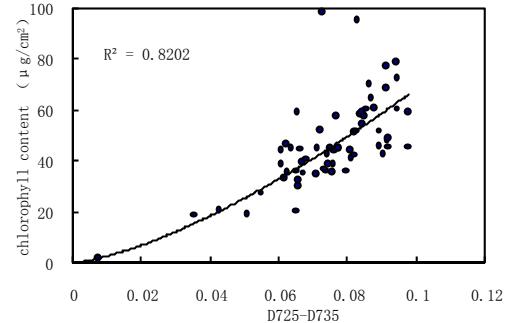


Figure 8. The relationship between chlorophyll content and the integration of the first derivative of reflectance at 725-735nm

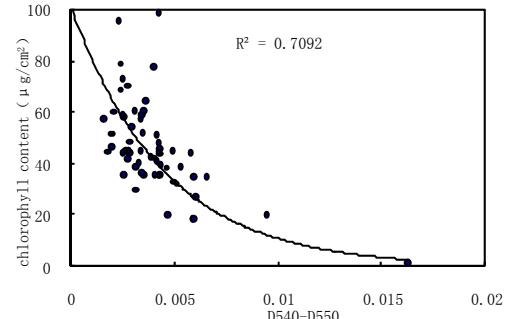


Figure 9. The relationship between chlorophyll content and the integration of the first derivative of reflectance at 540-550nm

4. DISCUSSION

The results indicate the optimal band range for estimating the mixed canopy chlorophyll content is 698-715nm region, which is the part of the red edge. For the first derivative of reflectance, the optimal bands range was D720-D735nm region and D535-D550nm region. The 740-900nm region can be used as reference band.

This study was performed based on LOPEX93 database. Further analysis is necessary to make sure that the optimal bands for estimating mixed canopy chlorophyll content can apply to other species unavailable in LOPEX93 database, especially conifer species.

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