Inversion of chlorophyll contents by use of hyperspectral CHRIS data based on radiative transfer model

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Abstract: Chlorophyll content, the most important pigment related to photosynthesis, is the key parameter for vegetation growth. The continuous spectrum characteristics of ground objects can be captured through hyperspectral remotely sensed data. In this study, based on the coniferous forest radiative transfer model, chlorophyll contents were inverted by use of hyperspectral CHRIS data in the coniferous forest coverage of Changbai Mountain Area. In addition, the sensitivity of LIBERTY model was analyzed. The experimental results validated that the reflectance simulation of different chlorophyll contents was coincided with that of the field measurement, and hyperspectral vegetation indices applied to the quantitative inversion of chlorophyll contents was feasible and accurate. This study presents a reasonable method of chlorophyll inversion for the coniferous forest, promotes the inversion precision, is of significance in coniferous forest monitoring.

Keywords: Radiative transfer model; Hyperspectral remote sensing; CHRIS; Inversion; Chlorophyll contents

1. Introduction

It is becoming a research focus in remote sensing field that hyperspectral remotely sensed images are applied to monitoring forest health status. Through determining chlorophyll contents of vegetation, the forest health diagnosis can be made. Hyperspectral remotely sensed data can provide forest biochemical indices, which have been successfully applied to nutrient cycling, productivity and species identification etc [1-3]. Hyperspectral remote sensing can also provide an effective means to detect plant structures and ecophysiological functions. Remote sensing is a rapid, non destructive method to detect vegetation nature [4-5], which can advance our understanding and modeling of plant ecophysiological processes. In addition, plant structures and chlorophyll contents strongly affect rates of photosynthesis, the differences of spectral reflectance characteristics of vegetation between visible and NIRS wavelengths intensely depend on chlorophyll and other pigment compositions, the spectral absorption range of carotene lies in 440-500nm, whereas the spectral absorption range of chlorophyll lies in 750-2500 nm, where the maximal absorption lies in 672nm [6]. It has been validated that the influence factor of absorption coefficient at that spectra mainly is the water content of leaf [7]. In the process of photosynthesis, chlorophyll and carotenoid absorb light, in which chlorophyll is the main material of light absorption, which directly affects plant photosynthesis. Healthy or unhealthy vegetation can appear to different reflectance maxima and different red edge parameters (wavelength position of the chlorophyll absorption maximum, red radiance, and NIR radiance) [8].

NDVI has been successfully applied to inversion of Leaf Area Index (LAI), leaf nitrogen
concentration, and the effective photosynthesis absorbance etc. [2,4,5], but the specific vegetation index cannot perfectly describe vegetation information, the advantages and disadvantages remains in all kinds of vegetation indices respectively. For this reason, it is necessary to choose different spectra to improve the linear relationship among vegetation index, chlorophyll contents and LAI, and remove saturation region, thus improving inversion precision of parameters. The relationship between vegetation indices and chlorophyll contents has been summarized [9]. Also, through combining with chlorophyll indices, the biomass of coniferous forest and grassland has been inverted by use of MODIS data [10]. As for physical model, PROSPECT [7] and LEAFMOD of broadleaved vegetation has been used to calculate chlorophyll contents [11]. Moreover, the biochemical parameters of vegetation in leaf scale (chlorophyll concentration) and the structural parameters in canopy scale (LAI) have been simulated by use of PROSPECT and SAIL [12]. Through combining with radiative transfer model of leaf and canopy, the relationship between canopy reflectance and chlorophyll contents has been established [13,14], as well as the coniferous forest LIBERTY [15] and chlorophyll contents model of water body [16]. The present methods for estimating forest aboveground biomass based on remote sensing techniques and the relative research advances have been analyzed [17]. In addition, there are ray track method and random model method about leaf model [2]. The spectral reflectance characteristics of vegetation are different in the visible wavelength, hyperspectral remote sensing can provide an effective means to monitor forest health status.

In this study, LIBERTY model, namely Leaf Incorporating Biochemistry Exhibiting Reflectance and Transmittance Yields model, will be applied to leaf reflectance simulation in the conditions of different chlorophyll contents, moisture contents, dry matter contents and leaf structural parameters etc. And the characteristic of LIBERTY model and its sensibility to inversion of chlorophyll contents will be analyzed. Moreover, the inversion results will be compared with that of the field measurement. Hyperspectral CHRIS data in the coniferous forest coverage of Changbai Mountain Area, on the basis of stripe noise removal, atmospheric radiative calibration and terrain correction [18], will be applied to inversion of chlorophyll contents based on LIBERTY model.

2. Study area and data
Changbai Mountian, located in the Southeast of Jilin province, China (127°40’~128°16’E, 41°35’~42°25’N), is the source of Songhua River, Tumen River and Yalu River. The average annual temperature is about 3-7°C, the average precipitation is about 700-1400mm, and the average duration of sunshine is about 2300 hours, belongs to continental mountain temperate climate. Changbai Mountain area, plenty of biological species, ecosystem integrity, is the most representative natural complex in the northern half of Eurasian continent.

CHRIS (Compact High Resolution Imaging Spectrometer), a multi-angular sensor, loaded on ESA small satellite platform PROBA (Project for On Board Autonomy) launched on October 22, 2001, sun synchronous orbit, orbit altitude of 615km, can provide high resolution and hyperspectral data. Five view zenith angles (0°, ±36°, ±55°) are provided though CCD imaging manner. A typical nadir image is 13km x13km in size at 17m spatial resolution. On the basis of stripe noise removal, atmospheric radiative calibration and terrain correction [18], CHRIS data can preferably respond to the reflectance characteristic to the earth’s surface.

3. Theory and methods
The coniferous forest LIBERTY model can well adopt to the concentration of leaf biochemical constituents (pigments, water, nitrogen, cellulose, and lignin etc.) [15]. Along with composite structural parameters for correcting the reflectance and transmittance of stacked leaf, LIBERTY provides a fine simulation to canopy structure, leaf reflectance and transmittance.

3.1. Radiative transfer of light within a leaf cell
Assuming that the internal cells of leaf are spherical particles, whose surface will scatter radiation according to Lambert’s cosine law and whose internal and external average reflectance coefficients are
defined as \( m_i \) and \( m_e \), respectively, and assuming that light absorption coefficient of individual leaf cell and radiative angle are \( k \) and \( \theta \) respectively, then, the total radiation reaching surface \( M \) will be equation (1):

\[
M = 2 \int_{\theta_1}^{\theta_2} e^{-kd \cos \theta} \cos \theta 2\pi \sin \theta \, d\theta
\]

\[
= 2[1-(kd+1)e^{-kd}]/(kd)^2
\]

(1)

and the total transmitted component \( \tau \) will be equation (2):

\[
\tau = (1-m_i)M/(1-m_eM)
\]

(2)

Therefore, the component radiation that is absorbed will be equation (3):

\[
1-\tau = (1-M)/(1-m_eM)
\]

(3)

3.2. Radiative transfer of light among leaves

Assuming that the leaf surface is horizontal, then we can define a set of parameters \( x_u \), \( x_a \), and \( x_d \), which represent the fraction of the radiation emerging from the interior of a cell in upward, adjacent, and downward directions respectively, and radiance emerging from inner surface of any cell is assumed to be isotropic, then, these parameters approximate the solid angle of the radiation, expressed as fractions of \( 4\pi \) steradians.

Because the initial reflected component of radiation contributing to \( R \) for unit incident radiation is \( 2xm_e \), in accordance with the interreflections among adjacent cells, the total radiation emerging from the leaf surface will be equation (4):

\[
R = \frac{2xm_e + x(1-2xm_e)\tau(1-m_eR)}{(1-m_eR)-(1-x)(1-m_e)\tau R}
\]

(4)

The equation above is quadratic in nature, therefore, the approximation of the root for \( R \) can be resolved by means of the Newton–Raphson iterative methodology.

4. Model sensitivity analysis

The spectral reflectance of different chlorophyll and water contents was simulated according to the coniferous forest model LIBERTY. Under the same conditions, the sensitivity of spectral reflectance to different chlorophyll contents was analyzed in the Vis wavelengths. On the one hand, with the increasing of chlorophyll contents, the spectral reflectance regularly decreased at the wavelength of 490nm and 800 nm; one the other hand, the spectral reflectance did not follow the changes of chlorophyll contents at the wavelength of 760 nm. At the same time, the simulation of spectral reflectance was compared with the field measured data, the maximal error was 0.058, and RMSE (Root Mean Square Error) was 0.020. Simulation and measured spectra comparison were shown in figure 1. We saw that the simulation errors increased when the wavelength was more than 800nm, and inversion of chlorophyll contents was coincided with the reflectance characteristic of vegetation when the wavelength was less than 800nm. Therefore, it followed that the spectral reflectance was sensitive to chlorophyll contents to some extent, inversion of chlorophyll contents could be carried out with CHRIS data.

5. Inversion of chlorophyll contents

On the basis of preprocessing of CHRIS data, the inversion relationship of chlorophyll contents was set up based on LIBERTY model, then LUT (Look-up-tables) of chlorophyll contents were achieved. LUT provided a simple radiative transfer method, which could be used to calculate radiative transfer pattern through a great deal of simulations. The optimal parameter arrays, through searching and ergod, were determined for matching LUT and spectra. Of course, LUT should be large enough \([19-21]\) for the purpose of obtaining high precision of the estimated parameters. The specific inversion procedure was described as follows:
According to the characteristic of LIBERTY model, firstly, a series of parameters including water, chlorophyll contents etc. were inputted into model; secondly, the reflectance characteristics were simulated; then, LUT of reflectance characteristics about different chlorophyll contents were set up; finally, the least square matchings were carried out between spectral reflectances corresponding to LUT and preprocessed CHRIS data including 18 wavelengths. In order to find out the solution to the inverse problem for a specific canopy, for each modeled reflectance spectra of LUT, \( RMSE \) between the measured and modeled spectra were calculated according to the following formula

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i} (R_{\text{obs}}(i) - R_{\text{m}}(i))^2}
\]

(5)

Where, \( R_{\text{obs}}(i) \) is the measured reflectance at wavelength \( i \), \( R_{\text{m}}(i) \) is the modeled reflectance at the same wavelength in the LUT, and \( n \) is the wavelength number. Inversion of chlorophyll contents in the study area is shown in figure 2.
6. Conclusions
In this study, based on the coniferous radiative transfer LIBERTY model, chlorophyll contents in the coniferous forest of Changbai Mountain Area were accurately inversed by use of CHRIS data in the Vis wavelengths, and the sensitivity of LIBERTY model was analyzed and validated. Through the comparisons between the simulated spectral reflectances and the field measured spectra, we found that the maximal error was 0.058 and RMSE was 0.020, and the inversion results of chlorophyll contents were reliable and coincided with the actual situation. Because of the high forest coverage and the heavy canopy densities in the study area, the chlorophyll contents are a high level. This study presents a reasonable method of chlorophyll inversion for the coniferous forest, promotes the inversion precision, is of significance in coniferous forest monitoring.

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