A Study on Estimation Method for CO_2 Uptake of Vegetation using Airborne Hyperspectral Remote Sensing

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Abstract: CO_2 uptake of vegetation is one of the important variables in order to estimate photosynthetic activity, plant growth and carbon budget estimations. The objective of this research was to develop a new estimation method of CO_2 uptake of vegetation based on airborne hyperspectral remote sensing measurements in combination with a photosynthetic rate curve model. In this study, a compact airborne spectrographic imager (CASI) was used to obtain image over a field that had been set up to study the CO_2 uptake of corn on August 7, 2002. Also, a field survey was conducted concurrently with the CASI overpass. As a field survey, chlorophyll *a* content, photosynthetic rate curve, Leaf area, dry biomass and light condition were measured. The developed estimation method for CO_2 uptake consists of three major parts: a linear mixture model, an enhanced big leaf model and a photosynthetic rate curve model. The Accuracy of this scheme indicates that CO_2 uptake of vegetation could be estimated by using airborne hyperspectral remote sensing data in combination with a physiological model.

Keywords: Hyperspectral remote sensing, CASI, Linear mixture model, Photosynthesis, Chlorophyll

1. Introduction

Recent evidence from leaf and canopy experiments has indicated that remote sensing in narrow spectral hands over the optical wavelengths is of great utility in quantifying plant pigment concentrations [1]. While most of the current research have addressed these through studies using individual leaves, collections of leaves, or small canopies grown in the laboratory under controlled conditions, relatively few have examined the applicability of different spectral variables, as we move from individual leaves to whole plant stands and plant canopy. Some researches with relatively simple or spatially homogenous canopy architecture have indicated that a few spectral variables are robust predictors of pigment concentrations from leaf to stand level. However, such variables can become unsuitable for vegetation with a more complex structure because of the effects of shadowing, nonphotosynthetic canopy elements and background reflectance on canopy spectral response. Demarez et al. (2000) found that, in addition to other external factors such as illumination geometry and atmospheric conditions, canopy architecture had an important control on the applicability of different spectral indices [2]. On the other hand, a study has hardly been done concerning the estimation of CO_2 uptake from Chl *a*, though the relation between Chl *a* content and photosynthetic activity is well known. This may be because, it is difficult to estimate abundance of Chl *a* in unit area from remote sensing data due to mixel problem and difficulty in defining the light condition and plant stress. Also, as one pixel size of remote sensing image is almost larger than a plant stand size, the measured reflectance of one pixel has effect of several factors, such as sunlit and shadow leaves or soil etc. In case of broad spatial resolution, it is necessary to overcome the mixel problem to estimate the abundance of biochemical content. The aim of this study was to develop an estimation method of CO_2 uptake by plant using airborne remote sensing in combination with a physiological model and liner mixture model.

2. Materials and Methods

1) Study area

The study area is the experimental field of the Field Production Science Center of University of Tokyo. It is located in the west of Tokyo, Japan (139°32’40”E, 35°43’50”N), where corn was grown on one experimental field. This field has fifty experimental plots: each measuring 7m x 8-m or 8m x 8-m, to which the fertilizer applications were randomly assigned. Each plot was made up of 22 rows of planted corn. The field data collection – ground samples and airborne measurements, were done 37days after sowing.

2) Data collection

Hyperspectral image at field scale was acquired by the Compact Airborne Spectrographic Imager (CASI) on August 2002 under clear sky condition within 30 min of solar noon. Spatial resolution of CASI image was 3.3m x 4.7m. Reference spectrum for 5 ground calibration sites were acquired using a hand-held GER 2600 spectroradiometer (Geophysical and Environmental Research) over flight at the same time in order to transform CASI’s radiance data to reflectance data. The calibration sites were spatially distributed throughout the study site and consisted of flat and homogenous areas. In addition, ground hyperspectral image at a stand scale was generated by using the portable hyperspectral imager, developed in our laboratory to simulate canopy reflectance. At the same time, the field and laboratory data were collected for biochemical and geochemical analysis, optical and biophysical measurements, along with other types of sensors’ measurements. Other relevant ground truth measurements include: (1) leaf chlorophyll concentration, (2) leaf reflectance, (3) SPAD value, (4) leaf area, (5) dry mass, (6) photosynthetic rate curve, (7) crop growth measures and (8) photosynthetic photon flux density (PPFD). Chl *a* concentrations per unit leaf area was measured spectrophotometrically for each leaf sample using DMF as a solvent and the equations and methodology for a leaf disk of 10 mm diameter [3]. The results from these sample determinations were then used together with the specific leaf area measurements to calculate the concentration of pigments per unit leaf area for each leaf. The correlation between Chl *a* content and SPAD value was examined.

3. Methodology

1) CO_2 uptake estimation method

An estimation method of CO_2 uptake in this study includes several processing steps, which are illustrated in Figure 1.

CO_2 uptake was estimated by both a specific CO_2 uptake per unit area and area ratio of vegetation in sub pixel .A specific CO_2 uptake per unit area was calculated based on light condition (PPFD) and a specific photosynthetic rate curve derived from enhanced big leaf model with Chl *a* content from hyperspectral image measured by the portable hyperspectral imager. Area ratio of vegetation at sub pixel level was estimated by a linear mixture model with both CASI image and the image generated by the portable hyperspectral imager.

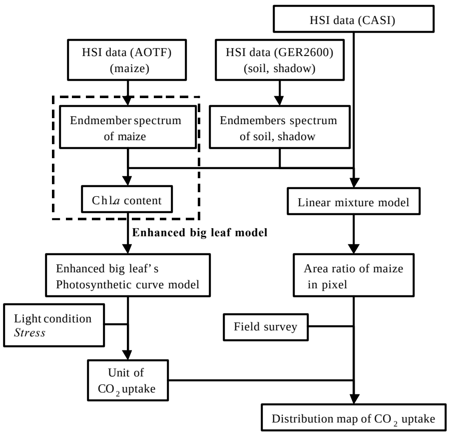


Fig. 1. Schematic overview of the estimation method of CO_2 uptake with photosynthetic rate model, liner mixture model and airborne hyperspectral image.

2) Photosynthetic rate curve model

CO_2 uptake was calculated by a photosynthetic rate curve model in this study. There are several photosynthetic rate curve models based on relationship between PPDF and assimilation rate [4]. These models are either rectangular hyperbolic type or non-rectangular hyperbolic type, according to current research. As a result of the initial study, non-rectangular hyperbolic type was chosen as the best suitable one to the actual photosynthetic rate curve of corn. Equation (1) shows that the photosynthetic rate curve model is of non-rectangular hyperbolic type.

$$NA = \frac{f \cdot PPDF + GA\max - \sqrt{4 \cdot f \cdot q \cdot PPDF \cdot GA\max}}{2q} - R \qquad (1)$$

where NA = net assimilation rate (µmol $CO_2/m^2/s$)
GAmax = maximum gross assimilation rate (µmol $CO_2/m^2/s$)
Ö = initial slope
È = convex degree of curve
PPFD = photosynthetic photon flux density (µmol photon/m^2/s)
R = Respiration (µmol $CO_2/m^2/s$)

In this model, important parameters are GAmax and R. As result of analysis, GAmax could be estimated by Chl *a* content per unit leaf area and also R could be estimated by GAmax. The multiple correlation coefficient were R^2=0.89 and R^2=0.74, respectively. Each Ö and È used was the measured value in this study.

3) Enhanced big leaf model

It was difficult to extract the representative spectrum of canopy from the airborne image, because size of one pixel of CASI image was larger than the size of a stand. One pixel was a mixel consisting of reflectance from several categories such as vegetation, soil and shadow. Moreover, reflectance of a stand changes according to the solar-vegetation-sensor geometry because of change in ratio of sunlit and shaded leaves. In addition to this, a stand reflectance is influenced a great deal by other surrounding stands, because reflectance of plant in near infrared range increases when leaves overlap. So, it is difficult to define canopy reflectance derived from a stand reflectance. On the other hand, it is necessary to relay the representative spectrum of vegetation to Chl *a* content per unit area to estimate a distribution map of CO_2 uptake with the photosynthetic rate curve model.

An enhanced big leaf model was investigated in this study. This model treats a canopy as a single leaf layer and could estimate both the representative spectrum of canopy for use in a mixel decomposition method and Chl *a* content for use in the photosynthetic rate curve model. Enhanced big leaf model consists of two components: (1) the representative spectrum of canopy was estimated by the measured stand reflectance in the laboratory where the geometry condition was reproduced similar to the CASI measurement and effect of surrounding stands, (2) Chl *a* content was estimated by the representative spectrum. Figure 2 stands for the flowchart of the enhanced big leaf model.

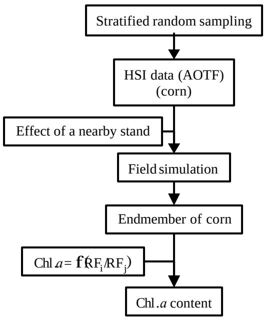


Fig. 2. the enhanced big leaf model.

Equation (2) shows an empirical equation derived from relationship between several hyperspectral images of stand in the laboratory and the measured Chl *a* content. This equation could estimate Chl *a* content from hyperspectral image in both sunlit and shadowed leaves.

$$Chl.a(\mu g/cm^2) = -24.5\,\mathrm{EXP}[RF_{725}/RF_{835}] + 75.3,\ R^2 = 0.64 \qquad (2)$$

where $Chl\ a$ = Chlorophyll a content(μg/cm^2)
RF_{725} = Reflectance at 725nm (%)
RF_{835} = Reflectance at 835nm (%)

Several stands were sampled from the field by stratified random sampling and this model was applied to these stands. Three sampling classes were assumed according to the growth measurement: (1) high, (2) middle, (3) low. As a result of study, it was found that the enhanced big leaf model could be applied to leaf layers ranging from top to the sixth layer. This is because the leaf area of the lower layers could not be measured or estimated by the measurement from the vertically above position.

4) Liner mixture model

As spatial resolution of CASI measurement in this study was larger than the size of a stand of corn, each pixel is a mixel, consisting of vegetation, soil and shadow in it. So, it is necessary to estimate ratio of vegetation in sub-pixel to apply our methodology. In this study, estimation of vegetation area ratio in each sub-pixel was calculated by a linear mixture model. The representative spectrum of both soil and shadow were measured by a hand-held GER 2600 spectroradiometer. On the other hand, the representative spectrum of corn was estimated from enhanced big leaf model applied to measurements from a portable hyperspectral imager. Equation (3) shows the linear mixture model.

$$RF(\lambda) = \sum_{i=1}^{k} a_i \cdot RF_i(\lambda), \quad \sum_{i=1}^{k} a_i = 1, \quad a_i \geq 0 \qquad (3)$$

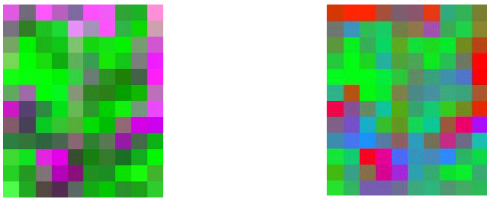
where $RF(\lambda)$ = Reflectance at λ nm (%)
i = Category
a_i = Area ratio of category i in sub-pixel
$RF_i(\lambda)$ = Reflectance of category i at λ nm (%)

The correlation between images was examined, and image combination with high correlation was excluded from calculation.

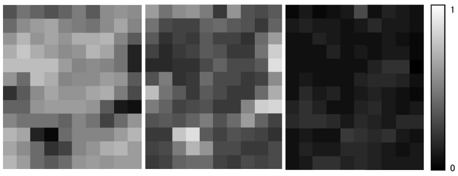
4. Results

1) Estimation of area ratio of vegetation in sub-pixel

The area ratio of corn in sub-pixel was estimated by the linear mixture model with the representative spectrum derived from the enhanced big leaf model. Figure 4 shows the result of the estimated area ratio of each category.



(a) (b)



Corn Soil Shadow

(c)

Fig. 4. (a) CASI real image of cornfield, (b) the pseudo color image of the result; R:G:B = soil: corn: shadow and the result of area ratio for each category.

The maximum RMSE in result was 2% for shadow. It was assumed that the pixel with an estimated high area ratio of corn consists of many high growth stands. Then, the accuracy of this result was evaluated by comparing the abundance of Chl *a* content per unit area above the sixth leaf layer in canopy. Table 1 stands for comparison of Chl *a* content estimated by the linear mixture model with the enhanced big leaf model and the field survey.

Table 1. Comparison of Chl *a* content between the results of the liner mixture model with enhanced big leaf model and the field survey.

	(g Chl.*a* /pixel)	(g Chl.*a* /m^2)
Field survey	8.670	0.548
Enhanced big leaf model	8.560	0.540

The accuracy was very good and Chl *a* content per unit area could be estimated from this method.

2) Estimation of distribution map of CO_2 uptake

The CO_2 uptake of the cornfield is actually affected by several environmental stresses such as water stress, heat stress etc. But environmental stresses were not considered in this study at this stage. The photosynthetic rate curve model needs PPFD to calculate the CO_2 uptake. PPDF was measured for the incident light condition of top canopy on August 7. Figure 5 shows the estimated daily CO_2 uptake of the representative spectrum of corn. Figure 6 shows the estimated distribution map of CO_2 uptake at the cornfield derived from this method.

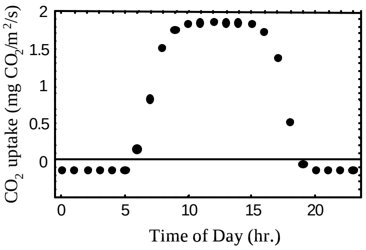


Fig. 5. The estimated daily CO_2 uptake of representative spectrum of corn on August 7.

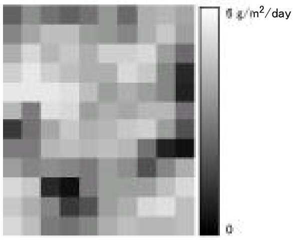


Fig. 6. The estimated distribution map of CO_2 uptake at the cornfield on August 7.

The accuracy of this result was evaluated by comparing the field measurements and the daily carbon assimilation per stand above the sixth leaf layer. Table 2 shows the values.

Table 2. Comparison of the daily carbon absorption between the field survey and the model.

	(g C/stand/day)
Field survey	0.776
This model	1.109

The results from this methodology shown an overestimation of 40% compared with the field survey, and can be attributed to the lack of consideration of the stresses and other factors.

5. Conclusions

The method for estimating the CO_2 uptake of vegetation using an airborne hyperspectral remote sensing, a physiological model and a linear mixture model was developed. But this method has several limitations including estimation of the leaf layer, definition of light condition and stress condition. Further research needs to be done in applying this model to many other crops, and developing parameters that could help include the estimation of stress conditions. Such efforts would help in linking hyperspectral data with the foliar concentrations, and by extension to vegetation.

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