Sensitivity Analysis of Net Primary Production Estimation using a Semi-empirical BRDF Model and Reflectance Observed by RC Helicopter for Japanese Cedar Forest

半経験 BRDF モデルと RC ヘリコプターによる
反射率観測データを用いた杉林の NPP 推定の感度分析

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Abstract : Among the existing global observing sensors, such as Terra/MODIS, NOAA/AVHRR, ADEOS-II/GLI, with a large field of view, there is a need to take Bidirectional Reflectance Distribution Function (BRDF) effect into account when using data of these sensors to analyze. For estimating the global NPP (Net Primary Production) from the spectral data of global observing sensors, and improving the accuracy of this estimation method simultaneously, it is necessary to know how this method was affected by BRDF effect, especially in the sensor's observation conditions. Using a Japanese cedar forest as the objective and a semi-empirical kernel-driven BRDF model (the RossThick-LiSparse model), this study analyzed BRDF effects on NPP estimation. The BRDF data of the forest used in this study were measured by a sensor onboard a radio-controlled helicopter with bidirectional reflectance factors (BRF) observations in July 2002. After validating the application of Ross-Li BRDF model to Japanese cedar forest, parameters of this model for the Japanese cedar forest were obtained, and used to retrieve reflectance for the nadir view and nadir illumination. With the retrieved reflectance, for the cedar forest, NPP estimations were affected by BRDF effects of approximately 11% under the GLI simulated observation conditions. This study also sought to validate the NPP estimation algorithm based on the pattern-decomposition-based vegetation index (VIPD) and photosynthetically active radiation (PAR) for multi-spectral sensor data. From the retrieved reflectance, the NPP of the study forest was estimated to be $0.36 \text{ kgCO}_2/\text{m}^2/\text{month}$. For comparison, forest surveys at the same study site have been conducted since the BRF observation. Using the ground-measured data, NPP was estimated to be $0.32 \text{ kgCO}_2/\text{m}^2/\text{month}$, which is in agreement with the preliminary result.

和文概要：全地球広域的に観測を行う衛星に搭載されるセンサーでは視野角の幅が広く、観測された分光反射率データには二方向性反射率 (BRDF: Bi-directional Reflectance Distribution Function) 影響があることが知られている。全球植生純一次生産量 (NPP: Net Primary Production) を求め、その精度を改善す

るためには、BRDF モデルを利用して、NPP の推定における BRDF の影響を評価する必要がある。本研究ではスギ林に着目し、無人ヘリコプターにより BRF (Bi-directional Reflectance Distribution Factors) 観測を行った。観測で得られた BRDF データより、BRDF モデルの適用性を検証した上で、パラメータを決定し、モデルから計算した反射率より杉スギ林の NPP を推定した。その結果は $0.36 \text{ kgCO}_2/\text{m}^2/\text{month}$ となり、森林調査の結果 $0.32 \text{ kgCO}_2/\text{m}^2/\text{month}$ と一致した。また、GLI センサーの観測状況をシミュレーションした上で、スギ林に対して、NPP の推定における BRDF の

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影響を調べた。その結果は11%であった。

1 . Introduction

The expansion and development of human activities have been accompanied by the tremendous consumption of fossil fuels, resulting in global environmental changes. Global warming, caused mainly by carbon dioxide from fossil fuel combustion, is perhaps the most serious problem humankind faces today. Research and development on solutions to the global warming problem include the control and decrease of CO_2 . Because vegetation has the ability to absorb CO_2 emitted to the atmosphere, research on the net primary production (NPP) of vegetation is necessary. NPP has been estimated by several models, including climate models (Leith, 1973 ; Uchijima and Seino, 1985) and ecological models (Monsi and Saeki, 1953 ; Potter et al., 1993) based on data observed by the International Biological Program (IBP). Currently, satellite observations can be used to monitor global vegetation, including vegetation coverage and activity (Potter et al., 1993 ; Huete et al., 1999 ; Awaya et al., 2004).

When estimating NPP from the data of satellite sensor, the normalized difference vegetation index (NDVI) is widely used, which is calculated from two reflectance channels: the visible red and near-infrared. To utilize the data from the multi-band sensor effectively, such as ADEOS-II/GLI, Terra/MODIS, a vegetation index (the VIPD) (Furumi et al., 1998, Hayashi et al., 1998) has been developed to estimate NPP, based on the pattern decomposition method (PDM: Fujiwara et al., 1996 ; Muramatsu et al., 2000 ; Daigo et al., 2004). With this index, the VIPD-based photosynthesis model was proposed to estimate photosynthesis and NPP, which is based on laboratory-measured leaves and canopy reflectance and photosynthesis (Furumi et al., 2005a). The estimated NPP by using this model and ground measured data agreed within the error at sparse vegetation in Mongolia by Xiong et al. (2005) with Landsat ETM⁺ data.

Landsat ETM⁺ has a field of view 5.7° for local area observation, but for global observations, many sensors have a very large field of view, such as the field of view of Terra/MODIS, NOAA/AVHRR, ADEOS-II/GLI is 55°, 55°, and 45°, respectively. The need for taking bidirectional reflectance distribution function (BRDF) effects into account in these global observing sensors data analysis, such as NPP estimation, is increasing being recognized (Wanner et al., 1995). When evaluating BRDF effect on NPP estimation or retrieving reflectance without BRDF effect, the suitable BRDF model is necessary. BRDF models are divided into three categories: empirical, semi-empirical, and physical. For fast computation requiring only a limited number of observations, semi-empirical BRDF models are regarded as robust models (Wanner et al., 1995). The kernel-driven model is one traditional semi-empirical model and is applicable to any kind of land cover (Hu et al., 1997), and this model has also been proposed for BRDF/albedo processing of data from the Moderate Resolution Imaging Spectro radiometer (MODIS) sensor of NASA's Earth Observing System (EOS ; Lucht et al., 2000). As one of the kernel-driven models, the reciprocal RossThick-LiSparse (Ross-Li) model, has shown good applications for various vegetations, including steppe grass and spruce forests (Wanner et al., 1997).

This research focused on analyzing the BRDF effect on NPP estimation of a typical Japanese cedar forest which is distributed widely throughout Japan. To realize it, bidirectional reflectance factor (BRF) observations were held to obtain the BRDF data of this forest by the sensor loaded on a radio-controlled helicopter. There is a need to validate the application of the Ross-Li BRDF model to a Japanese cedar forest by using these BRDF data and obtain the retrieved reflectance without BRDF effect. And then the NPP of this forest can be estimated from VIPD with the retrieved reflectance. For validating the result of NPP, namely, the application of this VIPD-based NPP estimation model to Japanese cedar forest, the estimated NPP of the

forest from VIPD is compared with the estimated NPPs from NDVI and from ground-measured data. Finally, as the work of the GLI sensor scientific researches, this paper also demonstrates the BRDF effect on NPP estimation of the objective under the simulated ADEOS-II/GLI observation conditions.

2 . Analysis Method

2.1 Ross-Li BRDF model

The Ross-Li BRDF model is formulated so that bidirectional reflectance is a linear combination of three terms weighted by three parameters (Ross, 1981 ; Li and Strahler, 1992 ; Roujean et al., 1992 ; Wanner et al., 1997) : an isotropic function f_{iso} accounting for bidirectional reflectance for the nadir view and overhead sun, a volume scattering f_{vol} function based on radiative transfer accounting for reflectance by a collection of randomly-dispersed facets, and a geometric function f_{geo} accounting for the effects of shadows and the geometrical structure of protrusions from a background surface as follows :

$$R(\theta, \vartheta, \phi) = f_{iso} + f_{vol}K_{vol}(\theta, \vartheta, \phi) + f_{geo}K_{geo}(\theta, \vartheta, \phi). \quad (1)$$

Here $R(\theta, \vartheta, \phi)$ is the BRDF, θ is the solar zenith angle, ϑ is the view zenith angle and ϕ is the view-sun relative azimuth angle. K_{vol} is the Ross-Thick kernel assuming a dense leaf canopy, and is the function of θ, ϑ, ϕ

$$K_{vol} = \frac{\left(\frac{\pi}{2} - \xi\right)\cos\xi + \sin\xi}{\cos\theta + \cos\vartheta} - \frac{\pi}{4}, \quad (2)$$

where ξ is the phase angle of scattering, and is written as

$$\cos\xi = \cos\theta\cos\vartheta + \sin\theta\sin\vartheta\cos\phi. \quad (3)$$

K_{geo} is the Li-Sparse kernel assuming a sparse ensemble of surface objects casting shadows on a Lambertian background as follows :

$$K_{geo} = O(\theta', \vartheta', \phi) - \sec\theta' - \sec\vartheta' + \frac{1}{2}(1 + \cos\xi')\sec\theta'\sec\vartheta' \quad (4)$$

$$O = \frac{1}{\pi}(t - \sin t \cos t)(\sec\theta' + \sec\vartheta'), \quad (5)$$

$$\cos t = \min\left\{1, \frac{h}{b} \frac{\sqrt{D^2 + (\tan\theta'\tan\vartheta'\sin\phi)^2}}{\sec\theta' + \sec\vartheta'}\right\}, \quad (6)$$

$$D = \sqrt{\tan^2\theta' + \tan^2\vartheta' - 2\tan\theta'\tan\vartheta'\cos\phi}, \quad (7)$$

$$\cos\xi' = \cos\theta'\cos\vartheta' + \sin\theta'\sin\vartheta'\cos\phi, \quad (8)$$

$$\theta' = \tan^{-1}\left(\frac{b}{r}\tan\theta\right) \quad \text{and} \quad \vartheta' = \tan^{-1}\left(\frac{b}{r}\tan\vartheta\right). \quad (9)$$

Above b is the crown vertical radius, r is the crown horizontal radius, and h is the height to the center of a crown. The crown relative height and shape parameters h/b and b/r are within the kernel and should be chosen two fixed values (Wanner et al., 1995). Figure 1 shows the shape of Li-Sparse kernel K_{geo} for four combinations of the parameters h/b and b/r with the view zenith was fixed to 30° in principal plane (the view-solar relative azimuth is 0°). It is obviously seen that the shapes of the kernel with parameters $b/r=2.5$ differ for the others and the shape of the kernels are almost the same even with the different values of h/b . That proves the shape of the crowns (b/r) affect the BRDF more than their relative height (h/b) (Wanner et al., 1995).

For the Ross-Li model calculation equations, if the parameters of f_x are decided, the BRDF depends on the K_{geo} and K_{vol} kernels. Before using this model, it is important to know the dependence of the kernels on the parameters in equations (2)-(9). Figure 2 demonstrates the shapes of the two kernels with various view zenith angles ; the LiSparse kernel values were computed for $h/b=2$ and $b/r=1$. In Figure 2, K_{vol} slopes upward with view zenith angle or solar zenith angle increasing. On the other hand, the shapes of K_{geo} are complexity. The shape of K_{geo} (view zenith is 60°) differs for the others and slopes

Figure 2 Ross-Li BRDF model kernels (left : Ross-Thick kernel ; right : Li-Sparse kernel) and solar zenith at various view zenith angles (0° , 30° , 45° , 60°) in principal plane ($b/r=1$, $h/b=2$)

Figure 1 In principal plane (view-solar relative azimuth of 0°), the values of Ross-Li BRDF model kernel K_{geo} for different combinations of parameters h/b and b/r . $h/b=2.5$, $b/r=2.5$ represents a tall prolate case; $h/b=2.5$, $b/r=0.75$ represents a tall oblate case; $h/b=1.5$, $b/r=2.5$ represents a low prolate case; $h/b=1.5$, $b/r=0.75$ represents a low oblate case; $h/b=2$, $b/r=1.0$ represents the spherical crowns are separated from the ground by half their diameter. The view zenith was set to 30° .

upward quickly with solar zenith. The shapes of K_{geo} (view zenith is 30° or 45°) slopes upward firstly and the maximum value displays at the hotspot (solar zenith is the same with view zenith) and then downward. Similar figures have been shown in Lucht et al (2000).

2.2 NPP estimation methods

In this study, for the same Japanese cedar forest, the net primary production (NPP) estimated from the normalized difference vegetation index (NDVI)

is used to compare with the result of NPP estimated from vegetation index based on the pattern decomposition method (VIPD). These two NPP estimation methods and the two vegetation indexes estimated by multi-spectral data are described in this section.

2.2.1 NPP estimation methods by VIPD

NPP can be calculated by subtracting the vegetation respiration (R_d) from the gross primary production (GPP; Box et al., 1989; Gower et al., 1999; Liu et al., 1999), as expressed by the following :

$$NPP = GPP - R_d. \quad (10)$$

To estimate GPP from multi-spectral data, Furumi et al (2005a) developed the following formula :

$$GPP = \int_0^{\text{month}} P(\text{PAR}(t), \text{VIPD}(t)) dt. \quad (11)$$

This formula expresses gross photosynthesis (P [mgCO_2]) as a function of the photosynthetically active radiation (PAR W/m^2) at a wavelength range of 400 to 700 nm and VIPD from multi-spectral data. To clarify this function expression, the light-photosynthesis curve and the reflectance of leaves and whole crowns of three plant species were measured (Furumi et al., 2005a). Here, t is time, and PAR (t) and VIPD (t) are the PAR and VIPD at the time t , respectively. P (PAR(t), VIPD (t)) [$\text{kgCO}_2/\text{m}^2/\text{s}$] is expressed approximately as follows :

$$P(PAR(t), VIPD(t)) = \frac{VIPD(t)}{VIPD_{std}} \times P_{std}(PAR(t)). \quad (12)$$

Here $VIPD_{std}$ is 0.561 and was determined from the average of five leaf samples. Four leaf samples were tea (*Camelia sinensis* var. *sinensis*) leaves, and one leaf was *Photinia Glabra* (Thunb). P_{std} (PAR (t)) [mgCO₂/m²/s] is the light-photosynthetic curve, expressed as follows :

$$P_{std}(PAR(t)) = \frac{P_{max} \times b \times PAR(t)}{1 + b \times PAR(t)}. \quad (13)$$

Here P_{max} is the maximum photosynthesis in a saturated region and b is the degree of the light-photosynthetic curve. From Eq. 13, it is clearly that photosynthesis increases as PAR becomes stronger within low PAR, but photosynthesis gradually approaches P_{max} when PAR becoming infinite. The b shows the curve as b increases and the increase in PAR leads rapidly to photosynthetic saturation. From the experimental data of five leaf samples and two trees (tea tree and *Photinia Glabra*), b is almost constant and the average value of b was 0.028 [m²/W], and P_{max} is approximately proportional to the VIPD as follows :

$$P_{max}[mgCO_2/m^2/s] = 0.918 \times VIPD. \quad (14)$$

Thus, the P_{max} of the standard photosynthetic curve P_{std} (PAR (t)) had value of 0.515 [mgCO₂/m²/s].

The VIPD is a vegetation index based on the pattern decomposition method (PDM). The PDM (Fujiwara et al., 1996 ; Muramatsu et al., 2000 ; Daigo et al., 2004) is a type of spectral mixture analysis in which the spectrum of each pixel is expressed as the linear sum of standard spectral patterns of water, vegetation, and soil. The VIPD represents the linear sum of the three pattern decomposition coefficients. The VIPD is based on the relationships between pattern decomposition coefficients and land cover ratios, and is used to study the vertical distribution of vegetation and the degree of vegetation vigor (Furumi et al., 1998) as follows :

$$VIPD = \frac{C_v - C_s - \frac{S_s}{\sum_{i=1}^n A_i} \times C_w - S_s}{S_v + S_s}. \quad (15)$$

Here, n is the number of bands and C_w , C_v , and C_s are the pattern decomposition coefficients of water, vegetation, and soil, respectively. A is the reflectance of band i . The sum of reflectance for all bands for the standard vegetation and standard soil sample are represented by S_v and S_s , respectively. These parameters are constant if the same wavelength bands are analyzed.

Vegetative respiration R_d is calculated from GPP and air temperature $T(^{\circ}C)$ by the following empirical equation (Chang, 1968) :

$$R_d = \frac{7.825 + 1.145 T(^{\circ}C)}{100} \times GPP. \quad (16)$$

2.2.2 NPP estimation methods by NDVI

To estimate NPP from satellite data, many researchers have developed light-use efficiency (LUE) model based on the concept that vegetation uses absorbed radiation energy to assimilate carbon (Monteith et al., 1965). The absorption ratio of photosynthetically active radiation absorbed by vegetation is estimated by the vegetation index NDVI. The NDVI is determined by a simple formula using only two satellite sensor bands : the red visible spectrum (e.g., GLI band 13) and near-infrared (NIR, e.g., GLI band 19). The NDVI is computed as follows :

$$NDVI = \frac{R_{nir} - R_{red}}{R_{nir} + R_{red}}, \quad (17)$$

where R_{red} and R_{nir} are the reflectance factors of red and NIR wavelengths, respectively. In this study, a simple LUE model was used to estimate NPP with NDVI, and environment stresses such as the vapor pressure, surface soil moisture, and air temperature, which was developed by Awaya et al. (2004). By this model, the global NPPs from 1988 to 1993 were successful estimated using NOAA images and meteorological data (Awaya et al., 2004). In this

LUE model, monthly NPP is estimated as follows :

$$NPP(gDW/m^2)=\sum f(T)f(SW)\cdot \epsilon \cdot NDVI \cdot SR, \quad (18)$$

where ϵ is the LUE of vegetation. Awaya et al. (2004) compared the integration of NDVI multiplied by solar radiation (SR) during the growth period (i. e., air temperature greater than or equal to 10°) with modeled NPP computed by the *Chikugo* model (a climatic potential NPP model) and estimated the average LUE ϵ of global vegetation as 0.494. The functions $f(T)$ and $f(SW)$ are the responses of photosynthesis to air temperature T and volumetric soil water content SW (fraction), respectively. In this study, for estimating NPP of the cedar forest in July, $f(T)$ was nearly 1. Since the objective is in the temperate zone with high SW , the stress is small and was neglected and $f(SW)$ was set to 1 (Awaya et al., 2004). The unit of NPP is Pg dry weight per m^2 (DW/m^2). Dry plant materials included approximately 45% carbon, and the NPP of 1 Pg DW/m^2 was equal to 0.45 Pg C/m^2 .

3 . Forest Survey

To validate the NPP estimated from the multi-spectral data, a Japanese cedar forest survey site (34.343° - 34.344° N, 136.024° - 136.026° E; WGS84) has been periodically surveyed following the helicopter-based observations of July 2002. The range of this forest survey site is 80×80 m and locates in the Kii Peninsula. This forest consists mainly of Japanese cedar and Japanese cypress at a ratio of 4 to 1, respectively. The trees were approximately 36 years old in 2002. Stand density is 1,732 trees/ha, and the average tree height was 11.43 m in 2002. This forest stand is located on a 30° slope facing southwest. Within the study area, 83 trees were chosen for growth-rate sampling. For the ongoing forest survey, sample trees are measured for height, the circumference at breast height (1.2 m above ground level), and amount of withering and quantity of the withered area. From these forest survey data, the NPP in July was estimated to be $0.32 \text{ kgCO}_2/m^2/$

month (the Appendix details the NPP estimation method).

4 . BRF Observations and simulated GLI observing conditions

4.1 BRF observations

The BRF was observed over the Japanese cedar forest on 18 July 2002. These observations measured the spectral reflectance of the same objective from different directions and the observation area has a grade of 30° . Figure 3 presents a simple representation of the BRF observations and Figure 4 shows the BRF observation points with latitude and longitude. Observations were conducted on three orbits (1-orbit, 2-orbit, and 3-orbit). The three orbits crossed at the observation object. The solar zenith of the

Figure 3 BRF observation techniques

Figure 4 Helicopter location during the BRF observations. The sun locates in the east. The lines cross at the observation location.

three orbits ranged from 47.8 to 42.9, 32.7 to 28.7, and 23.1 to 19.9°, respectively, and the view zenith ranged from 3.3 to 60.0°. The spectral reflectance of the objective was measured by a radio-spectrometer onboard the radio-controlled (RC) helicopter. The radio-spectrometer had a wavelength range of 520 to 920 nm with a spectral resolution of 1 nm. A white board was loaded on the helicopter and used to calibrate radiation from the ground as part of the reflectance measurement process. The radio-spectrometer had a 20° field of view and flight altitude of approximately 40 m. Thus, the instantaneous field of view was 14×14 m. A digital camera was used to photograph each observation area.

4.2 Simulated GLI observation conditions

To make clear the BRDF effect on NPP estimation in GLI sensor's observing conditions, it is necessary to simulate the conditions of GLI observation. GLI is designed for frequent global observations of reflected solar radiation from the Earth's surfaces including both land and ocean. The GLI has 23 bands in the visible and near-infrared regions, six bands in the short-wave infrared region (SWIR), and seven bands in middle and thermal infrared region, allowing for multi-spectral observations. The GLI has a spectral range of 375 to 12,500 nm. The helicopter-based sensor (for the BRF observations) had a wavelength range of 520 to 920 nm. Thus, five GLI bands were selected for NPP estimations. The center wavelengths of these five bands were 545, 678, 710, 763, and 865nm, respectively. The scanning angle of the GLI was 0–45°.

5 . Results and Discussion

5.1 Reflectance measured by BRF observations

For the BRF observations, reflectance varied with the view and illumination angles. Figure 5 compares reflectances (dotted and dashed lines) measured by the helicopter-mounted sensor from different directions (BRF observations) and the

Figure 5 The dashed and dotted lines show the reflectance measured by the helicopter-mounted sensor from different directions (BRF observations). The solid line indicates the reflectance from a cedar leaf measured by the ground-based FieldSpecFR spectral radiometer. The reflectance shown by the dashed line was measured at a solar zenith of 47.8°, view zenith of 50.6°, view-sun relative azimuth angle of 0°, and phase angle of 2.8°; the reflectance of the dotted line was measured at a solar zenith of 47.2°, view zenith of 60.0°, view-sun relative azimuth angle of 0°, and phase angle of 12.8°.

reflectance (solid line) of a cedar leaf measured using the FieldSpecFR (made by ASD: Analytical Spectral Devices, Inc) from the nadir view indoor with halogen lamp as the light source (the field of view was full of the cedar leaves). Reflectances measured by the helicopter-mounted sensor were clearly much lower than the reflectance measured at ground level by the FieldSpecFR that measured a non-shadowed illuminated object from a nadir view. Although other factors exist (e.g., the difference in measuring height and the density of cedar leaves), the BRDF effect is certain. Furthermore, because of the different sensor zenith and solar zenith for the same objective, the BRF observations had different reflectances. Figure 6 shows the shape of the reflectances measured by the BRF observations with the phase angles (ξ) which can be calculated by equation (3) for the five corresponding GLI bands. Note that reflectance decreased as the phase angle increased even when the reflectance decreased at different rates. Bands 8, 13, 15, 17, and 19 had rates

Figure 6 The relationship between the phase angle and the original reflectance for the five selected GLI bands with central wavelengths of 545, 678, 710, 763, and 865 nm, respectively.

of decrease of 82.1, 74.1, 72.4, 76.2, and 77.2%, respectively, which is also explained that the BRDF effect is different with various wavelength.

5.2 Parameters for the Ross-Li BRDF model

As noted in section 2, the parameter f_{iso} of the Ross-Li model describes the nadir sun reflectance and view reflectance, without BRDF effects. The f_x

parameters for the BRDF model were estimated using the BRF observation data. The kernels K_x depend only on the viewing and illumination geometry from equations (2)–(9). Parameters f_x could then be fit using all the reflectances obtained from the BRF observations and the kernels K_x . Table 1 lists the results.

Table 1 Ross-Li model parameters based on the BRF observation date

GLI Band	Central Wavelength	f_{iso} (Standard Error)	f_{geo} (Standard Error)	f_{vol} (Standard Error)
band 8	545nm	0.0544 (2.9%)	0.0188 (6.1%)	0.0376 (14.2%)
band 13	678nm	0.0220 (3.0%)	0.0070 (6.8%)	0.0118 (18.8%)
band 15	710nm	0.0276 (2.9%)	0.0082 (7.1%)	0.0172 (15.8%)
band 17	763nm	0.2216 (2.3%)	0.0601 (6.2%)	0.1234 (14.0%)
band 19	865nm	0.2245 (2.7%)	0.0607 (7.1%)	0.1191 (16.8%)

Figure 7 The relationship between the original reflectance and reflectance computed by the Ross-Li model using the BRF observations. The asymptotic standard errors were 1.3, 1.1, 1.5, 1.6, and 1.6% for bands 8, 13, 15, 17, and 19, respectively.

5.3 Validation of the Ross-Li BRDF model

Although Ross-Li BRDF model has been proposed for BRDF/albedo processing of data from the MODIS and has good application to vegetation, the research of Japanese cedar forest has little. An effective BRDF model must be capable of accurately representing the shape of naturally occurring BRDFs (Lucht et al., 2000). Figure 7 compares reflectances calculated by the Ross-Li model with the fitted parameters (shown in Table 1) and the original observed reflectances in the five corresponding GLI channels (8, 13, 15, 17, 19); the relationship is almost linear at $y=x$. The asymptotic standard error of fitting varied with wavelength and was 1.6, 1.6, 1.5, 1.1, and 1.3% for bands 8, 13, 15, 17, and 19, respectively. Even though there were some slight deviations, the modeled reflectances generally followed the observed values. These results proved the Ross-Li BRDF model had a good application to the Japanese cedar forest.

5.4 NPP estimation

The retrieved reflectances (f_{iso}) shown in Table 1 were then used to calculate the NDVI (defined by Eq. (17)) and the VIPD (defined by Eq. (15)). The VIPD equaled 0.55 and the NDVI was 0.82.

Using the VIPD (0.55), NPP could be estimated by equations (10)–(16). The solar radiation (SR) over 24 hours for one month (July 2002) was measured on the roof of a building at Nara Women's University; these data were used to calculate monthly mean PAR data over 24 hours. However, NPP is overestimated when monthly mean PAR over 24 hours is used because plants photosynthesize only during the daytime. Xiong et al. (2005) approximated the time-integral of photosynthesis using monthly mean PAR over the effective day length of vegetation photosynthesis (h); this length was defined as the time between sunrise and sunset (H) minus 2.0 hours. The monthly mean value of h was 12 hours. Therefore, the mean value of solar irradiance for h was 400 W/m^2 . The mean air temperature in Nara in July is 25.0°C . The NPP was thus $0.36 \text{ kgCO}_2/\text{m}^2/$

month.

As noted above, the sum of the photosynthetically active radiation $PAR(t)$ for one month (July 2002) was 539.09 MJ/m^2 . Using equations (18) and (17), the NDVI was calculated as 0.82, and NPP was estimated as $0.32 \text{ kgCO}_2/\text{m}^2/\text{month}$; this result is close to the result using the VIPD.

Both NPP estimations agree with the NPP ($0.32 \text{ kgCO}_2/\text{m}^2/\text{month}$) estimated from forest survey data which was described in section 3.

5.5 Sensitivity of NPP to the BRDF

With the Ross-Li BRDF model, the retrieved reflectances from BRDF observations could be obtained without BRDF effects. Next, the effects of BRDF on the reflectance values of BRDF observations as well as on the VIPD and ultimately the NPP could be examined.

The phase angle (ξ) parameter was used to evaluate BRDF effects after validating the application of this parameter. To match the GLI observation conditions, the view zenith ranged from 0 to 45° . And for the mainly vegetation covered area ($60^\circ\text{N} \sim 60^\circ\text{S}$), with the GLI observing time (approximately 11:00 am, local time), the solar zenith ranged from 10 to 60° . For the simple computation, supposing the relative azimuth angle as $0, 45, 90, 135$, and 180° , with all combinations of the solar zenith and view zenith, the kernels K_x could be calculated by equations (2)–(9). Applying the values of the parameters (f_x) being shown in Table 1, reflectance for the five bands were computed. Figure 8 shows the relationship between phase angle and reflectance corresponding to the five bands. When the phase angle increased, reflectance of the corresponding bands generally decreased, although the range of reflectance with the same phase angle is wide in principal plane (relative azimuth is 0°). Moreover, the maximum decreasing rate of reflectance ($1 - \text{the ratio of the mean reflectance for the maximum phase angle to the mean reflectance for minimum phase angle}$) varied with wavelength. For example, when the relative azimuth is 90° , the maximum

Figure 8 The relationship of the reflectance and phase angle based on the simulated GLI observation conditions, where the solar zenith and view zenith were set between 10–60° and 0–45°, respectively. With all solar zenith and view zenith combinations, the phase angle ranged from 0 to 120°, and the relative azimuth was set to 0°, 45°, 90°, 135°, and 180°.

decreasing rates are 70, 69, 67, 59, and 60% corresponding to bands 8, 13, 15, 17, and 19, respectively. In other words, different bands have different BRDF effects. Generally, for the same phase angle, the reflectance values were very close. These results show that the phase angle is a suitable parameter for evaluating BRDF effects within the simulated

GLI observing conditions.

Using the phase angle as a parameter, the effects of BRDF on the VIPD and NDVI determined from the BRDF observations were analyzed. Figure 9 displays the relationships between the phase angle and VIPD or NDVI. For Figure 9, the VIPD and NDVI values were calculated from the reflectances mea-

Figure 9 The relationship between the phase angle and NDVI (left) or VIPD (right). Here, the VIPDs and NDVIs were calculated from the reflectance that was measured during the BRF observations. The phase angle was divided into 5°, increments in the same range of values as the average values and standard deviations for the VIPD and NDVI.

sured during the BRF observations. The smallest BRDF effects occurred when the phase angle was 0°, i.e., the solar and view positions aligned. The mean VIPD for the BRF observations was 0.50; as noted above, this value was smaller than that of the VIPD (0.55) calculated from the retrieved reflectance. Clearly, the VIPD increased as the phase angle decreased. In contrast, the mean NDVI from the BRF observations was 0.83, which was larger than that (0.82) calculated from the retrieved reflectance. Furthermore, the NDVI had a downward tendency with decreasing phase angle, because the rate of reflectance change in the near-infrared band was smaller than that in the red band with a decrease in phase angle.

Data from the BRF observations were available only for July at the Japanese cedar forest; thus, the VIPD, NDVI, and NPP for other months could not be calculated. The BRDF effects can change with variations in the solar angle caused by differences in the time of day, season, and latitude of observations. To understand BRDF effects over an entire year, the simulated GLI observation conditions can be used to calculate the VIPD and NDVI and subsequently the NPP. GLI observations of Japan at approximately 11:00 Japan Standard Time (JST) on the 15th day of every month were analyzed. The solar zenith and azimuth could be determined from the date and the time. The GLI has a view zenith of 0–45° and view azimuth of 270° and 90°. The re-

flectances were calculated using the Ross-Li model and the parameter values listed in Table 1. From equations (10)–(18), to estimate the value of NPP for one year, it is necessary to consider seasonal variations (air temperature and solar radiation). This paper especially examines BRDF effects on NPP estimations. For brevity, the same air temperature (25.0°C) and solar irradiation (400 W/m²) were used to estimate NPP for one year. The NDVI and NPP values for one year were determined. Figure 10 shows the results. Figure 11 lists the NPP estimated from the VIPD. The NDVI in Figure 10 and VIPD in Figure 11 have the same tendency as those shown in Figure 9. When the phase angle increased, the VIPD decreased. In contrast, the NDVI slightly increased when the phase angle increased. In Figures 10 and 11, the phase angle changes from 10.1 to 84.2°, and the NPP calculated from the NDVI (shown in Figure 10 on the right) changes within (0.32, 0.33), increasing 4%. Furthermore, the NPP calculated from the VIPD (shown in Figure 11 on the right) changes within (0.35, 0.31), decreasing 11%. These results show that NPP estimation using the VIPD is more sensitive to the BRDF effects than that using the NDVI. Furumi et al (1998) concluded that the NDVI is almost constant regardless of change in the thickness of leaves because reflectance in the visible wavelengths almost did not change even when leaves overlapped; however, in the near-infrared, reflectance increased with an increase in the thick-

Figure 10 The influence of BRDF effects over one year on the vegetation index NDVI at one BRF observation site (34.3435°N, 136.0248°E ; WGS84) and NPP estimated from the NDVI. The conditions were based on the GLI observation conditions.

Figure 11 The influence of BRDF effects over one year on the vegetation index VIPD at one BRF observation site (34.3435°N, 136.0248°E ; WGS84) and NPP estimated from the VIPD. The conditions were based on the GLI observation conditions.

ness of overlapped leaves until becoming saturated (Yamamoto et al., 1995 ; Furumi et al., 1998). This conclusion suggests that NDVI has a low sensitivity to the thickness of leaves, such as that in a forest with dense leaves, and tall trees. The thickness of leaves changes with the changes in the solar zenith or view zenith. On the other hand, from equation (17), BRDF effect on NDVI is restrained because both denominator and numerator include the two bands (the red band and near-infrared band), and the differences in BRDF effect in these two bands lead to increase of NDVI with the decrease of phase angle. In equation (15), BRDF effect on VIPD is expressed by the sum of the reflectance of all bands. So the VIPD is more sensitive to the BRDF effects than the NDVI.

6 . Conclusion

This paper has described the successful application of a semi-empirical BRDF model, the Ross-Li BRDF model to Japanese cedar forest. Moreover, the retrieved reflectances were obtained using BRDF data from BRF observations with the BRDF model, and the parameters of this model for the Japanese cedar forest were determined. Using the retrieved reflectances, the NDVI and VIPD vegetation indexes were calculated, and NPP values were subsequently estimated as 0.36 kgCO₂/m²/month by the VIPD and 0.32 kgCO₂/m²/month by the NDVI. These two NPPs were very close. On the other hand, with the data from the forest survey, NPP of the same forest was roughly calculated as 0.32 kgCO₂/m²/month in July. Therefore, the NPP esti-

mated from the BRF observations agreed with the NPP calculated from the forest survey data. These results confirm that the NPP estimation method using the VIPD can be used for the Japanese cedar forest.

Using the Ross-Li BRDF model, BRDF effects on NPP estimation under the simulated GLI observation conditions were also evaluated. Results showed that the VIPD and NDVI tended to vary differently in response to changes in the phase angle. The NDVI increased as the phase angle decreased due to differences in the BRDF effects in the visible and near-infrared bands. Furthermore, with changes in the phase angle, the NPP calculated from the NDVI and VIPD changed by 4 and 11%, respectively. This finding should be considered in future studies seeking to improve the accuracy of global NPP estimations using GLI data. We also plan to conduct further NPP estimations using Landsat/ETM⁺ and MODIS data and to compare these results with NPP estimations based on GLI data.

For the next few years, the survey of the Japanese cedar forest described in this study will continue in order to obtain more accurate ground data related to tree growth.

Appendix

The following data are being collected at the forest site: tree circumference at breast height (1.2 m above ground level), tree height, amount of the withering, and quantity of dead leaves. Although more than 2 years have passed since data collection began, there are not yet enough data to accurately estimate NPP. However, we can roughly estimate NPP (Furumi et al., 2005b).

Since July 2002, we have measured the circumference of 84 sample trees at breast height. The average growth ratio of the circumference at breast height is calculated as follows:

The mean tree circumferences at breast height were 0.589 m in November 2002 and 0.613 m in November 2004. The average tree diameters at

breast height (DBH) were 0.188 m in November 2002 and 0.195 m in November 2004. The average growth ratio was 4.1% in 2 years. Sample trees had an average height of 11.43 m in 2002. Assuming that the growth ratio at a given tree height changes in the same manner as the circumference at breast height, the average increase in height was determined to be 0.47 m.

Furthermore, assuming that tree trunks are conical in shape, the volume of the trunk can be calculated as follows:

$$V_{cone} = \left(\frac{h}{h-1.2} \times \frac{DBH}{2} \right)^2 \times h \times \frac{\pi}{3} \quad (19)$$

However, assuming a conical trunk shape will actually underestimate the volume value. Cedar trees show the following linear relationship between measured trunk volumes and those estimated by assuming a conical shape:

$$V_{trunk} = 1.288 \times V_{cone} - 0.001 \quad (20)$$

For calculating the dry weight, a sample tree was selected and measured as 293.8 kg/m³. From this sample tree, the relationship between the weight of above-ground parts of the tree and the trunk could be expressed as follows:

$$W_{above-ground} = 1.18 \times W_{trunk} + 5.24 \quad (21)$$

For the tree roots, the ratio of the dry weight of aboveground parts to the dry weight of underground parts (T/F) was assumed to be 3.5.

From the DBH, the average height, and the equation below, the variation in dry weight of one tree from July 2002 to July 2004 was calculated as follows:

$$W_{2002} = [(0.132 m^3 \times 1.288 - 0.001) \times 293.8 kg/m^3 \times 1.18 + 5.24] \times \left(1 + \frac{1}{3.5} \right) = 82.08 kg \quad (22)$$

$$W_{2004} = [(0.147 m^3 \times 1.288 - 0.001) \times 293.8 kg/m^3 \times 1.18 + 5.24] \times \left(1 + \frac{1}{3.5} \right) = 90.40 kg \quad (23)$$

$$\Delta W_{two-year} = 8.32 \Rightarrow \Delta W_{one-year} = 4.16 \text{ kg/year} \quad (24)$$

Because there are 1,108 trees in the study area ($80 \times 80 \text{ m}$), with a 30° slope, in the unit area, the NPP of the tree was calculated as:

$$NPP = 4.16 \times 1108 \times \frac{1}{(80 \times \cos 30)^\circ} = 0.96 \text{ kg/m}^2/\text{year} \quad (25)$$

From the photosynthesis $6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$, and the drying process $\text{C}_6\text{H}_{12}\text{O}_6 \rightarrow \text{C}_6\text{H}_{10}\text{O}_5 + \text{H}_2\text{O}$ ($\text{C}_6\text{H}_{12}\text{O}_6 : 6\text{CO}_2 = 27 : 44$), the organic dry weight was converted into a carbon dioxide value of $1.56 \text{ kg/m}^2/\text{year}$. Obviously, the value of NPP in summer at the study site is higher than that in winter. Thus, from the ratio of global solar irradiance in July to the yearlong global solar irradiance (not including the months in which the mean temperature was below 10.0°C), the NPP value for July was estimated as $0.32 \text{ kgCO}_2/\text{m}^2/\text{month}$.

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