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Estimation of Forest LAI in Close Canopy Situation Using Optical Remote Sensing Data

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Abstract : Although there have been several attempts to estimate forest LAI using optical remote sensor data, there are still not enough evidences whether the NDVI is effective to estimate forest LAI, particularly in fully closed canopy situation. In this study, we have conducted a simple correlation analysis between LAI and spectral reflectance at two different settings: 1) laboratory spectral measurements on the multiple-layers of leaf samples and 2) Landsat ETM+ reflectance in the close canopy forest stands with field-measured LAI. In both cases, the correlation coefficients between LAI and spectral reflectance were higher in short-wave infrared (SWIR) and visible wavelength regions. Although the near-IR reflectance showed positive correlations with LAI, the correlations strength is weaker than in SWIR and visible region. The higher correlations were found with the spectral reflectance data measured on the simulated vegetation samples than with the ETM+ reflectance on the actual forests. In addition, there was no significant correlation between the forest LAI and NDVI, in particular when the LAI values were larger than three. The SWIR reflectance may be important factor to improve the potential of optical remote sensor data to estimate forest LAI in close canopy situation.

Key Words : LAI, forest, spectral reflectance, spectro-radiometer, close canopy, ETM+.

1. Introduction

Forest leaf area index (LAI) has been one of important structural variables to understand the process of forest ecosystems and can be used to measure the activities and the production of plant ecosystem (Pierce and Running, 1988; Bonan, 1993). The measurement of forest LAI on the ground is very difficult and requires a great amount of time and efforts (Gower *et al.*, 1999). Plant canopy is composed of leaves, which is a direct source of the energy-matter interactions that can be observed by earth-observing remote sensing systems. Therefore, LAI has been a very attractive variable of interest in vegetative remote sensing. There have been many attempts to estimate LAI using various types of remote sensor data since the early stage of space remote sensing (Badwhar *et al.*, 1986; Peterson *et al.*, 1987; Turner *et al.*, 1999). Remote sensing estimation of LAI has been primarily based on the empirical relationship between the field-measured LAI and sensor observed spectral responses (Curran *et al.*,

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1992; Peddle *et al.*, 1999).

As a single value to represent the remotely sensed spectral responses of green leaves, spectral vegetation indices, such as normalized difference vegetation index (NDVI) or simple ratio, are frequently used to indirectly estimate LAI. NDVI has been a popular index to estimate LAI across diverse ecosystems. However, large portion of such studies to estimate LAI using NDVI were dealing with semi-arid vegetation and agricultural systems where the canopy closure is less than 100%. Recent studies have shown that NDVI may not be very sensitive to LAI in particular at the forest ecosystem having the close canopy condition that the LAI value is relatively high (Chen and Cihlar 1996, Turner *et al.* 1999; Lee at al., 2003, 2004).

Although there were several studies dealing with the remote sensing estimation of LAI in forest, the study sites were generally not close canopy situation (Turner *et al.*, 1999; Lefsky *et al.*, 2001). The objectives of this study are to analyse the relationship between spectral reflectance and LAI in fully canopy condition and to find an alternative to estimate LAI in forest where the canopy closure and LAI values are high. The forest vegetation has relatively dense canopy closure in Korea as well as many other temperate and tropical forests around the world. Considering the environmental value of these forest ecosystems, more effective and accurate method to estimate forest LAI would be very beneficial.

2. Methods

1) Laboratory spectral measurements on simulated LAI samples

Before attempting to analyze the actual satellite imagery along with field-measured LAI data, we decided to analyse the relationship between the reflectance spectra and LAI in close canopy situation. For this purpose, a laboratory experiment was conducted to measure the reflectance spectra of the vegetation samples using a portable spectro-radiometer.

Vegetation samples of various level of LAI were prepared by stacking multiple-layers of evergreen broad leaves (*Euonymus japonicus* Thunb). As seen in Fig. 1, the multiple-layers of leaves fill the field of view (FOV) of the spectro-radiometer. Since each leaf has approximately the same size and the total leaf area can be easily obtained. LAI value of each sample is calculated from the total leaf area divided by the area of FOV. Total of 15 samples were prepared and LAI value ranges from 1 to 6 with an interval of approximately 0.25. Every sample was fully covered by these leaves to simulate the close canopy situation and there was no influence from the background soil.

Reflectance spectra were measured using a portable spectro-radiometer (GER 2600), which can measure spectral reflectance over the wavelength region between 350nm and 2,500nm. Spectral reflectance were measured at 140cm height with a 10 degree FOV lens. The actual size of the FOV for the spectro-radiometer did not exactly correspond to simple trigonometry calculation and it looks an ellipse shape with diameters of about 24cm and 18cm.

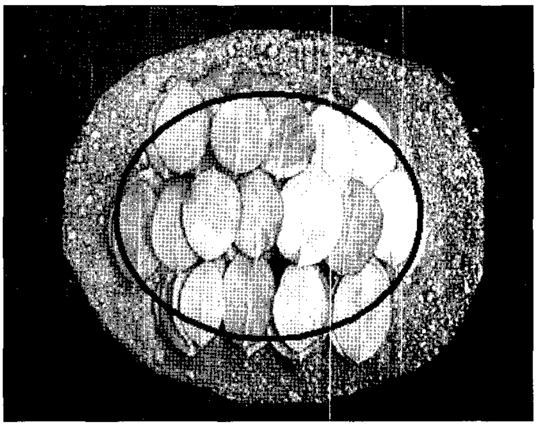

Fig. 1. A vegetation sample to simulate known LAI within the FOV (black line) of the spectro-radiometer.

At each measurement, the spectro-radiometer actually provides percent reflectance value for each of 612 continuous bands over the wavelength from 350nm and 2,500nm. The simplest statistical investigation was the calculation of a band-by-band correlation between spectral reflectance value and LAI of the leaf-sample. Because each wavelength band represented a different combination of spectral strengths and weaknesses, discrepancies in correlation at particular wavelengths might provide us particular spectral qualities for estimating LAI.

We also compared LAI values of the vegetation sample with NDVI. Since spectral measurements by the spectro-radiometer give us many adjacent bands within the spectrum of red and near infrared wavelengths, several combinations of NDVI calculation are possible. However, as Teillet *et al.* (1997) pointed out, NDVI is not very sensitive to the location of any particular wavelength within the red and near-infrared spectra. Two spectral reflectance measurements at 655nm and 846nm were used to calculate NDVI.

2) ETM+ reflectance and field-measured LAI

In addition to the laboratory experiment of the spectral measurement on several vegetation samples, further analysis was carried out to compare the field-measured LAI and reflectance spectra obtained from Landsat ETM+ data. The study area was a relatively small watershed in Kyungan River, covering an area of approximately 500 km^2 of mixed coniferous and deciduous forests near the Seoul metropolitan area. The temperate mixed forest in the study area has diverse group of species composition and stand ages between 20 to 50 years old and the canopy closure is over 80%. One third of the forest lands are coniferous plantation stands (*Pinus koraiensis, Pinus rigida, and Larix leptolepis*) and the remaining two third of forests are natural stands of mixed deciduous species.

During the growing season of 2003, 30 ground sample plots were selected and species, LAI, stand density, and stand height were measured. LAI values were measured using an optical device (LiCor LAI 2000). Each plot has an area of 20×20 m^2 and includes five subplots for LAI measurement within it. All subplot measurements were averaged to provide a single value for the LAI at each plot. Plot locations were determined using a differential global positioning system (GPS). To minimize any discrepancies due to the phenological variation of leaf development, the field measurements were conducted as close to the date of satellite data acquisition. Although the May 8^{th} of satellite data acquisition is slightly earlier than the field measurement (late June to early July), we believe that it did not cause any serious problem since the leaf development in 2003 started very early and the canopy condition between the May 8^{th} and the late June of the same year was not much different.

For the study, we obtained Landsat-7 ETM+ data acquired on May 8, 2003. ETM+ images were geo-referenced, radiometrically calibrated, and converted to surface reflectance value. Initially, ETM+ images were geo-referenced to the local plane rectangular coordinates by using a set of ground control points obtained from the 1:5,000 scale topographic maps. Although DN value represents a certain amount of radiometric quantity that was reflected from the canopy, it also includes partial signal originated by atmospheric attenuation. After raw DN value was converted to the sensor-received radiance by applying gain and offset coefficients, the radiance value was transformed to percent reflectance after the atmospheric correction. Although atmospheric correction has become a critical step for deriving any quantitative variables of biophysical parameters from optical remote sensing data, it is rather complex and difficult to apply the absolute correction of atmospheric effects on multispectral data such as ETM+. We used MODTRAN radiative transfer code to calculate the atmospheric transmittance and other terms using a standard atmospheric model and local meteorological data for the atmospheric correction.

After the geometric and radiometric correction of the spectral imagery, a vector file of the forest stand maps, that were produced by Korean Forestry Research Institute using 1:15,000 scale aerial photographs, was overlaid to the geo-rectified ETM+ reflectance data. Three or four pixels spanning the boundary of each field-measured forest plot were extracted and their reflectance values were averaged. Due to the high spatial autocorrelation, the variation of adjacent pixels was very low to overcome the problem of the sub-pixel error from the geometric registration.

3. Results and Discussions

Correlation coefficients between the simulated LAI and spectral reflectance obtained from the spectro-radiometer were highly variable by wavelength (Fig. 2). In general, the only positive correlations were in the nearIR regions. For all other spectral regions, correlation coefficients are negative. Correlation coefficients between LAI and spectral reflectance in visible and short-wave infrared (SWIR) wavelengths were much stronger than in near infrared regions.

In this experiment where the vegetation samples simulated the completely closed canopy, the relationship between LAI and spectral values seems to exhibit rather unique pattern. It is interesting to note that the contrast between the NIR and the other region. The NIR wavelength region between 700 and 1,300nm has been known for the essential part of deriving several vegetative features, such as LAI. However, under the close canopy situation, the strength of correlation in the NIR region was weaker than the other wavelength region. These results suggest that the characteristics of close canopy vegetation system may be explained by additional wavelengths other than the near-IR wavelengths. In particular, the SWIR region and, perhaps, red-edge region near 700 nm show strong potential to be used for estimating LAI in close canopy situation.

NDVI has been the most widely used spectral vegetation index to estimate LAI over diverse biomes. As has been reported in many previous studies, the relationship between the sample LAI and NDVI derived from laboratory spectral measurement appears relatively strong (Fig. 3). However, the positive correlation looks apparent only when the

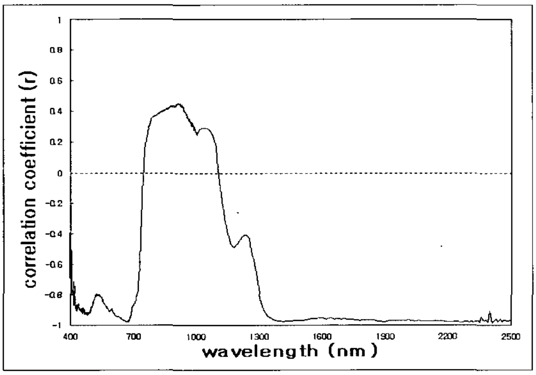

Fig. 2. The correlation coefficients between the LAI values of the vegetation samples and spectral reflectance measured by the spectro-radiometer in the laboratory.

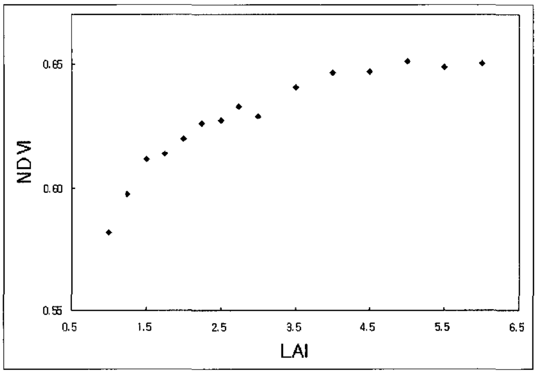

Fig. 3. Relationship between the LAI of vegetation sample and NDVI that was derived from the laboratory spectral measurements at 655nm and 846nm.

sample LAI value is relatively small. When the LAI is larger than three, the relationship becomes saturated and there is no significant correlation between the LAI and NDVI.

Forest LAI values measured in 30 forest plots over the study area in the Kyungan watershed were relatively high in which the lowest LAI was 2.74 and the highest was 7.11. LAI of coniferous plantation stands were higher than mixed deciduous stands. The LAI variation was very low at the mixed deciduous stands as compared to the pine plantation stands. Field measured LAI was initially analyzed by its correlation with atmospherically corrected ETM+ reflectance values. Correlation coefficients between the spectral reflectance and the field measured LAI were very low for all plots when both species groups were combined (Table 1). Forest LAI varies by several factors of stand structure, such as species, stand density, canopy closure, diameter at breast height (DBH), tree height, and understory vegetation. Considering the diverse groups of species composition and relatively high dense forest canopy in the study area, such low correlations would not be surprising.

When we calculated the correlation coefficient separately for each of two species groups of coniferous and mixed deciduous forest, the absolute value of correlation coefficients increased at the coniferous forest. The coniferous plantation stands are rather homogeneous in species composition. The variation of LAI in these stands is mainly due to the tree size and stand density. As seen in the previous laboratory experiment, only NIR band (band 4) shows the positive correlation although correlation was very weak. There are negative correlations between the field-measured LAI and ETM+ reflectance in visible and SWIR bands. The negative correlation between the LAI and SWIR reflectance may explained by several factors including leaf moisture content, shadow effects among trees, and understory vegetation (Nemani *et al.*, 1993).

No significant correlations were found at deciduous stands. Unlike the coniferous plantation stands, the mixed deciduous stands showed very little variation in the field measured LAI value (mean=4.33, std=0.78). The subtle differences in the actual forest LAI values were thought to be the cause of such relatively low correlation.

Fig. 4 shows the relationship between the field-measured LAI and NDVI that was derived from the two ETM+ band 3 and band 4. In overall, the correlation between the forest LAI and NDVI is very weak. The forest stands were almost close canopy and their LAI values were larger than three. The lack of relationship between NDVI and LAI at high LAI vegetation has been noted in several studies (Chen and Cihlar 1996, Turner *et al.* 1999, Cohen *et al.*

Table 1. Correlation coefficients between field measured LAI and spectral reflectance of ETM+ bands.

Spectral band	all	conifers	deciduous
NDVI	0.228	0.508	-0.125
Band 1	-0.114	-0.320	0.056
Band 2	-0.097	-0.302	0.070
Band 3	-0.287	-0.560	0.055
Band 4	0.086	0.296	-0.179
Band 5	-0.233	-0.277	-0.286
Band 7	-0.270	-0.574	-0.075

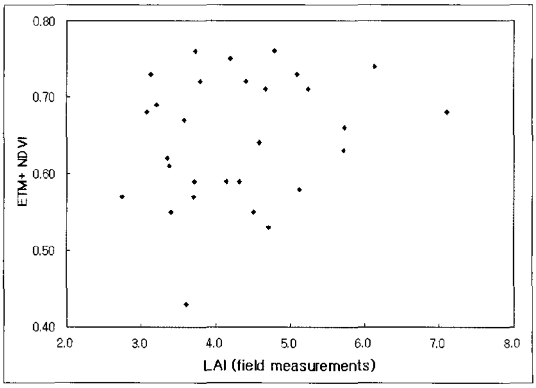

Fig. 4. Relationship between the field-measured LAI and NDVI that was derived from the two ETM+ bands.

2003). For over two decades, NDVI has been a popular index with which to estimate LAI across diverse systems, but these results suggest that other indices may be more appropriate. Fortunately, numerous recent studies have noted a strong contribution of SWIR bands to the strength of relationships between reflectance and LAI (Nemani *et al.* 1993, Brown *et al.* 2000).

The primary difference between the spectro-radiometer and ETM+ spectral measurements is that the spectro-radiometer data has more and narrow bands. Strength of correlation coefficients were much stronger with the spectro-radiometer data although the general pattern of correlations were similar. The low correlation between field-measured LAI and ETM+ reflectance is probably related to the structure of forest stand where the tree species, size, and density vary. Further, the LAI values at the study sites is larger than three while the simulated leaf samples measured by the spectro-radiometer have the LAI values ranging from one to six. The laboratory vegetation samples were basically horizontal layering of flat leaves, which did not quite reflect the three dimensional structure of forest stand. Further experiment will be focused to measure reflectance spectra on the vegetation samples that has vertical structure of leaf distribution.

4. Conclusions

Forest LAI has been a key variable to understand the productivity and process of forest ecosystem at various spatial and time scales. However, there are not enough evidences that spectral reflectance in visible and near-IR region (and NDVI based on these two spectral signals) will be enough to estimate the forest LAI, in particular at the close canopy situation. In this study, we have conducted a simple correlation analysis between LAI and spectral reflectance at two different settings. From the spectral reflectance data measured by the spectro-radiometer over the multiple-layers of laboratory leaf samples, the stronger correlations were found at the visible and SWIR wavelength region. Although positive correlations were noticed at the near-IR wavelength region, they were not as strong as the other wavelength spectrum.

When we extended the comparison to the actual forest stands, the correlations between the field measured LAI and ETM+ reflectance were very weak. Significant correlations were only found at the coniferous plantation stands. The overall patterns of correlation was somewhat similar to the result obtained from the spectro-radiometer experiment. In both cases, the correlations with the SWIR and red reflectance were higher than the near-IR reflectance.

Although the SWIR spectrum has been known for its relationship with the moisture content of vegetation, it has been rare to verify the information content of SWIR to derive biophysical characteristics of vegetation. Since the launch of the Landsat-1 in 1972, only a few satellite sensors have comprised spectral bands that have been operating at SWIR spectrum. Landsat Thematic Mapper (TM, ETM+) is probably the most well-known sensor that has SWIR spectral bands. In recent years, there has been increasing number of new satellite sensors (such as MODIS, ASTER, SPOT) that include SWIR bands. We expect that there will be additional studies to evaluate the potential of SWIR bands for extracting vegetative information.

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