WHAT IS THE ACTUAL RELATIONSHIP BETWEEN LAI AND VI IN A DECIDUOUS BROADLEAF FOREST?

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ABSTRACT:

The Moderate Resolution Imaging Spectroradiometer (MODIS) is the primary NASA Earth Observing System instrument monitoring the seasonality of global terrestrial vegetation. MODIS products, such as the MODIS Vegetation Index (VI), Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Leaf Area Index (LAI), are commonly used for evaluating the ecological variables. In this study, we examined the LAI–VI relationship based on *in situ* data. Two VIs as NDVI and EVI were measured from a hemispherical spectroradiometer (HSSR) at the study site, Takayama in Central Japan. LAI data were observed based on phenology shoot and litter trap approaches from 2005-2006. To compare *in situ* NDVI and EVI to *in situ* LAI, we investigated two patterns: a single relationship using all of the data and a double relationship of two periods (growing to saturation and saturation to leaf-fall). These equations from the regression function were used to apply to MODIS NDVI and EVI 8 day composite data for LAI estimation. MODSI EVI presents better results than does MODSI NDVI and is a fairly good match to *in situ* LAI, with r^2= 0.89 and 0.94, respectively. Furthermore, $NDVI_{MODIS}$ yielded seasonally earlier LAI values than did *in situ* LAI estimates, as it included the forest floor. The double relationship improved the accuracy of LAI estimates over that of the single relationship. The overestimation error of single-relationship $NDVI_{MODIS}$ was reduced, and forest floor reflectance in the early growing season was decreased, thus fitting better to *in situ* LAI values. The fluctuation of both $NDVI_{MODIS}$ and EVI_{MODIS} winter LAI estimates derived from the single relationship was considerably removed, and both were close to reflecting the actual leafless condition of winter. Moreover, MODIS LAI 8 day composite images were applied to compare among the results for validation. It was showed that MODIS LAI provided overestimated LAI than usual. However, validation with further comparisons is still needed.

1. INTRODUCTION

Leaf area index (LAI) is an important biophysical variables affecting to the forest ecosystems, defined as the projected area of leaves per unit of ground area (Ross, 1981). It is a required input parameter for the ecological models since it used to evaluate the photosynthesis for gross primary productivity estimation (Bonan, 1993; Landsberg and Waring, 1997; Muraoka and Koizumi, 2005). To obtain LAI value, there are both direct and indirect measurements. The allometric methods and using the instruments methods as LAI-2000, Tracing Radiation and Architecture of Canopies: TRAC and etc. have been used to directly estimate *in situ* LAI (Norman and Campbell, 1989; Chen et al., 1997; Gower et al., 1999; Leblance and Chen, 2001). It can obtain the LAI value accurately. However, these methods are time, manpower and financial consuming. Another measurement uses the remote sensing data which have been widely applied to estimate LAI. Even though it contains the effect of atmospheric conditions and cloud contamination, it provides up-to-date data and extends the spatial scale from one point data to broad area. Moreover, it can reduce the disadvantage points of the direct measurements.

The applications of remote sensing data provide the possibility of the relationship between vegetation index (VI) and LAI (Nemami et al., 1993; Myneni et al., 1995). Normalized difference vegetation index (NDVI) is one of the most commonly used VI for estimating LAI and primary production. Several studies showed the relationship between LAI and NDVI in grasslands, croplands, shurblands and a few in forests (Friedl et al., 1994; Law and Waring, 1994; Chen and Cihlar 1996; Cohen et al., 2003). It reported that NDVI has considerable sensitive to LAI. Moreover, it showed the saturated point when the LAI value is large in case of the deciduous forest (Birky, 2001). Another VI generally used in current time is enhanced vegetation index (EVI). It was improved to reduce the effect of background reflectance and atmospheric errors (Huete et al., 2002). It was also more sensitive to dense vegetation than NDVI. Chen et al. (2005) conveyed that EVI estimated LAI better than NDVI for coniferous forest. However, it detected the maximum LAI earlier than *in situ* LAI in corn field (Chen et al., 2006).

In those studies, they have only utilized VI data from the satellite images based. It still contains the uncertainties of reliable data because of the cloud contamination, snow covering, atmospheric effects as well as the missing recorded data. All mentioned causes lead to the influence of the relationship between LAI and VI. To obtain the general and robust LAI-VI relationship, the relationship should be examined by using long-term continuous *in situ* data both LAI and VI. In this study, we used *in situ* VI measured by spectroradiometer (Nagai et al., 2010) and *in situ* LAI by leaf seasonality and litter trap approaches (Nasahara et al., 2008) at the deciduous broadleaf forest. Those LAI approaches can estimate LAI precisely and seasonal change of each species. The use of *in situ* data is to make us more clear understanding the relationship between LAI and VI.

The main objective of this study is to investigate the actual relationship between LAI and VI (NDVI and EVI) based on *in situ* data at the deciduous broadleaf forest, major vegetation type in Japan. We compared *in situ* LAI data with *in situ* NDVI and EVI data to obtain the regression equations. Then, these equations were applied to NDVI and EVI based satellite image for validating the accuracy assessment. The results of this study suppose to support the theoretical interpretation for the relationship between LAI and VI that may enriches the improvement of the results in the ecological aspects.

2. MATERIALS AND METHODS

2.1 Study sites

The study site was located in a deciduous broadleaf forest, the major type of vegetation in Japan, in Takayama, central Japan (36°8′46″N, 137°25′23″E; 1,420 m altitude), at a site where meteorological and ecological parameters have been observed continuously at a flux tower since 1993 (Saigusa et al., 2002), which belongs to AsiaFlux (http://asisflux.yonsie.kr/) and Japan Long Term Ecological Research Network (JaLTER: http://www.jalter.org). During 2005–2006, the mean annual air temperature and annual precipitation were 6.67°C and 2199 mm, respectively. Snow cover during the winter (December–April) was approximately 1 m in depth. The forest canopy was dominated by *Quercus crispula* and *Betula ermanii*, with heights of 18–20 m. The forest floor was covered by evergreen dwarf bamboo, *Sasa senanensis* (Ito et al., 2005; Ohtsuka et al., 2005). The data used in this study were from 2005–2006.

2.2 LAI observations

LAI data were obtained by the leaf seasonality and litter trap approaches (Nasahara et al., 2008). We used the leaf seasonality approach during the leaf-expansion period. The shoots from the dominant species were selected to measure the number of all leaves and the leaves size (length and width). For the litter trap approach, it was observed LAI data during leaf-fall period. The litter including leaves, branches, seeds and so on were seized, but the leaves were selected and sorted according to each species. The method to estimate LAI was referred from Nasahara et al. (2008). By integrating these two approaches, the LAI data were extrapolated to cover throughout the leaf expansion to –fall period.

However, the study site was covered by the forest floor, *Sasa senanensis*, under the canopy. The LAI value of *Sasa senanensis* was assumed to be average 1.71 (Sakai et al., 2002). It was mostly stable for whole year (Nishimura et al., 2004). In this study, the LAI value was used from 2005 to 2006 excluding the forest floor since it cannot observe by the satellite images.

2.3 Vegetation index observations

To observe NDVI and EVI, we installed a hemispherical spectroradiometer (HSSR) system to monitor spectral features of vegetation conditions at fine-temporal and fine-spectral resolutions (Nagai et al., 2010). The spectral range was 300–1100 nm, with a 3.3-nm spectral interval and 10-nm half-band width (MS-700, Eko Instruments Co. Ltd., Tokyo, Japan). The computer-controlled rotating stage (CHS-AR, Hayasaka Rikoh Co. Ltd., Sapporo, Japan) could be directed upward and downward of the spectroradiometer every 10 min (Nishida, 2007). Spectral data measured with this instrumentation avoid cloud contamination and atmospheric noise effects. Using HSSR spectral reflectance data, we calculated NDVI and EVI, using the 620–670-nm spectral range for the red band (*RED*), 841–876 nm for the near-infrared band (*NIR*), and 459–479 nm for the blue band (*BLUE*). These spectral bands correspond to MODIS bands 1, 2 and 3, respectively. NDVI (Rouse et al., 1973) and EVI (Huete et al., 2002) are common VIs used to calculate LAI from the following equations:

$$\mathrm{NDVI} = (NIR - RED)/(NIR + RED) \quad (1)$$

$$\mathrm{EVI} = G[(NIR - RED)/(NIR + C_1(RED) - C_2(BLUE) + L)] \quad (2)$$

where C_1 and C_2 are coefficients of aerosol resistance and L is a canopy background adjustment. Normally, the values of G, L, C_1, and C_2 are 2.5, 1, 6, and 7.5, respectively. NDVI and EVI values calculated from HSSR were referred to as $\mathrm{NDVI}_{\mathrm{HSSR}}$ and $\mathrm{EVI}_{\mathrm{HSSR}}$. LAI data collected by leaf seasonality and litter trap approaches on the same date were then compared to $\mathrm{NDVI}_{\mathrm{HSSR}}$ and $\mathrm{EVI}_{\mathrm{HSSR}}$.

2.4 Remote sensing images analysis

We used MODerate resolution Imaging Spectroradiometer (MODIS) images in this study because of their significant temporal and areal coverage. To avoid the effects of cloud contamination and atmospheric aerosols, we selected composite images to increase the quality of spectral reflectance (Holben, 1986; van Leeuwen et al., 1999). Recently, MODIS products are provided for the different applications. For NDVI and EVI data, we used MODIS/Terra Vegetation Indices 16-day L3 Global 1 km SIN Grid. Both VIs were used to evaluate LAI data based on the LAI–VI relationship from *in situ* data.

MODIS/Terra+Aqua Leaf Area Index/FPAR 8-day L4 Global 1 km SIN Grid products were used to obtain LAI data. MODIS LAI is based on a look-up-table method based on a six-biome land cover structural classification. The LAI product assigns a value between 0.0 and 8.0 to each 1-km cell of the global grid database.

All MODIS products were downloaded from the NASA Land Processes Distributed Active Archive Center using the NASA Warehouse Inventory Search Tool (https://wist.echo.nasa.gov/api/). The data were collected in 2005–2006. We extracted the single pixel corresponding to each study site from the satellite image. The footprint of this study site, Takayama, was approximately 1 km^2 (Saigusa et al., 2002), which was the same as the 1-km spatial resolution of the satellite image. MODIS NDVI and EVI are henceforth referred to as $\mathrm{NDVI}_{\mathrm{MODIS}}$, and $\mathrm{EVI}_{\mathrm{MODIS}}$, respectively.

In addition, we investigated the LAI–VI relationship by dividing it into two periods (leaf-expansion to –saturation period and leaf-saturation to –senescence period) and comparing these data against all other data. Since the seasonal patterns of LAI-VI during leaf-expansion and -senescence periods were different. Beginning, the VI value increasingly responses to the phonological leaf cycle in growing season, whereas it gradually decreases in the autumn. The criteria defining the separation of the periods were (1) the day of the VI maximum value and (2) the day of year between days 182–243 that were in the range of period to reach the saturation stage. Days prior to the separation

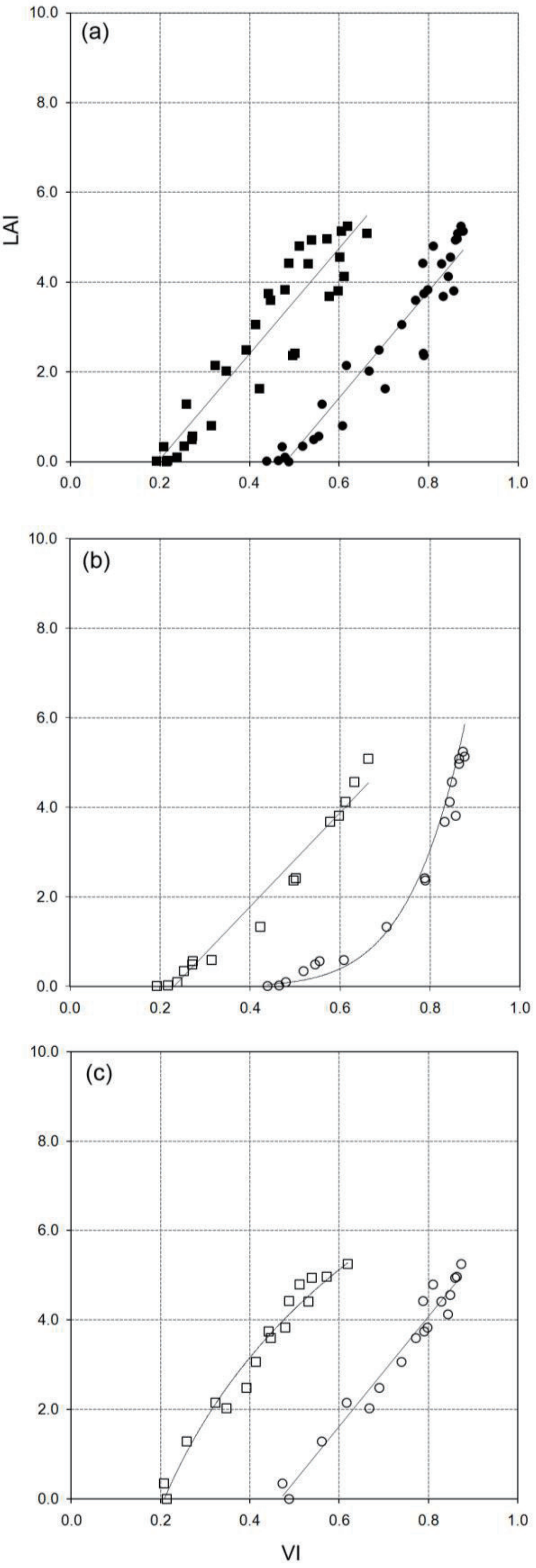

Figure 1. The scatter plot of *in situ* LAI and *in situ* VI (solid circle is NDVI and solid rectangular is EVI) from (a) single relationship and double relationship (b) leaf-expansion to saturation period, and (c) saturation to leaf-senescence period. The solid lines show the regression functions of each relationship.

day were in the leaf-expansion period relationship, whereas those after that day were in the leaf-senescence period relationship.

3. RESULTS AND DISCUSSION

3.1 *In situ* LAI - VI_{HSSR} relationship

The LAI–$NDVI_{HSSR}$ and LAI–EVI_{HSSR} relationships were examined to assign the appropriate VI_{HSSR} for LAI estimation. Figure 1a shows the linear relationship between LAI and both $NDVI_{HSSR}$ and EVI_{HSSR} throughout the year. With r^2 = 0.91, $NDVI_{HSSR}$ showed a higher significant relationship to LAI than did EVI_{HSSR} (r^2 = 0.87).

Figure 1b and 1c show the double relationships. Before the saturation day (leaf-expansion period), the LAI–$NDVI_{HSSR}$ relationship is a clear exponential curve, with r^2 = 0.88, responding to the mixture of forest floor and forest canopy reflectance. $NDVI_{HSSR}$ increases slightly with large increases in LAI. It also shows a saturation point, as the $NDVI_{HSSR}$ value is greater than 0.8, whereas the LAI range is 3–5. Lüdeke et al. (1991) also stated that LAI value of forest greater than 3 cannot be detected by NDVI data, which presented the maximum value of 0.8, whereas $NDVI_{HSSR}$ had the linear relationship in the leaf-senescence period. The LAI–EVI_{HSSR} relationship is precisely linear, with the r^2 value is high (0.97). However, it still shows saturation point (congregated point) error, as EVI_{HSSR} is close to 0.6.

After the saturation day (leaf-senescence period), the difference in the LAI–$NDVI_{HSSR}$ and LAI–EVI_{HSSR} relationships are illustrated in the linear relationship of LAI to $NDVI_{HSSR}$ and its clear logarithmical relationship to EVI_{HSSR}. The r^2 values are 0.96 and 0.97, respectively. Wang et al. (2005) stated the similar results of the linear relationship between LAI and NDVI in senescence period. These results led us to realize clearly the actual relationship between LAI and NDVI. For EVI_{HSSR}, the value decreases, whereas the LAI value does not change much until close to the leaf-fall period. Since EVI_{HSSR} accounts for LAI values that respond to the leaf phonological cycle, the leaf is getting bigger in the leaf expansion responding to EVI_{HSSR} value increases linearly. During the leaf senescence period, leaf color changes from green to yellow or red in the deciduous broadleaf forest that affecting to the EVI_{HSSR} value decreases, whereas the LAI values do not much change. Wang et al. (2005) depicted that EVI can indicate the seasonal variations of LAI throughout the year, even it showed the low agreement with LAI during the leaf senescence period due to the limited data and some error of LAI from model computation. The results of this study supported that *in situ* data are the proper evidence to show the relationship between LAI and VI.

3.2 LAI estimation by VI_{MODIS}

To evaluate the relationship of LAI and VI_{HSSR}, we applied the $NDVI_{HSSR}$ and EVI_{HSSR} regression equations to $NDVI_{MODIS}$ and EVI_{MODIS} from the satellite images. Figure 2 shows the seasonal pattern of LAI estimated from the LAI-VI_{HSSR} relationship. LAI derived from $NDVI_{MODIS}$ overestimates *in situ* LAI. EVI_{MODIS} presents better results than $NDVI_{MODIS}$ based on the linear relationship and is a fairly good match to *in situ* LAI. The overestimation errors were rechecked by comparing HSSR data to MODIS product data (Fig. 3). $NDVI_{MODIS}$ values were mostly higher than those of $NDVI_{HSSR}$ that affected the LAI overestimations (r^2 = 0.81), whereas EVI fit closely to a one-to-

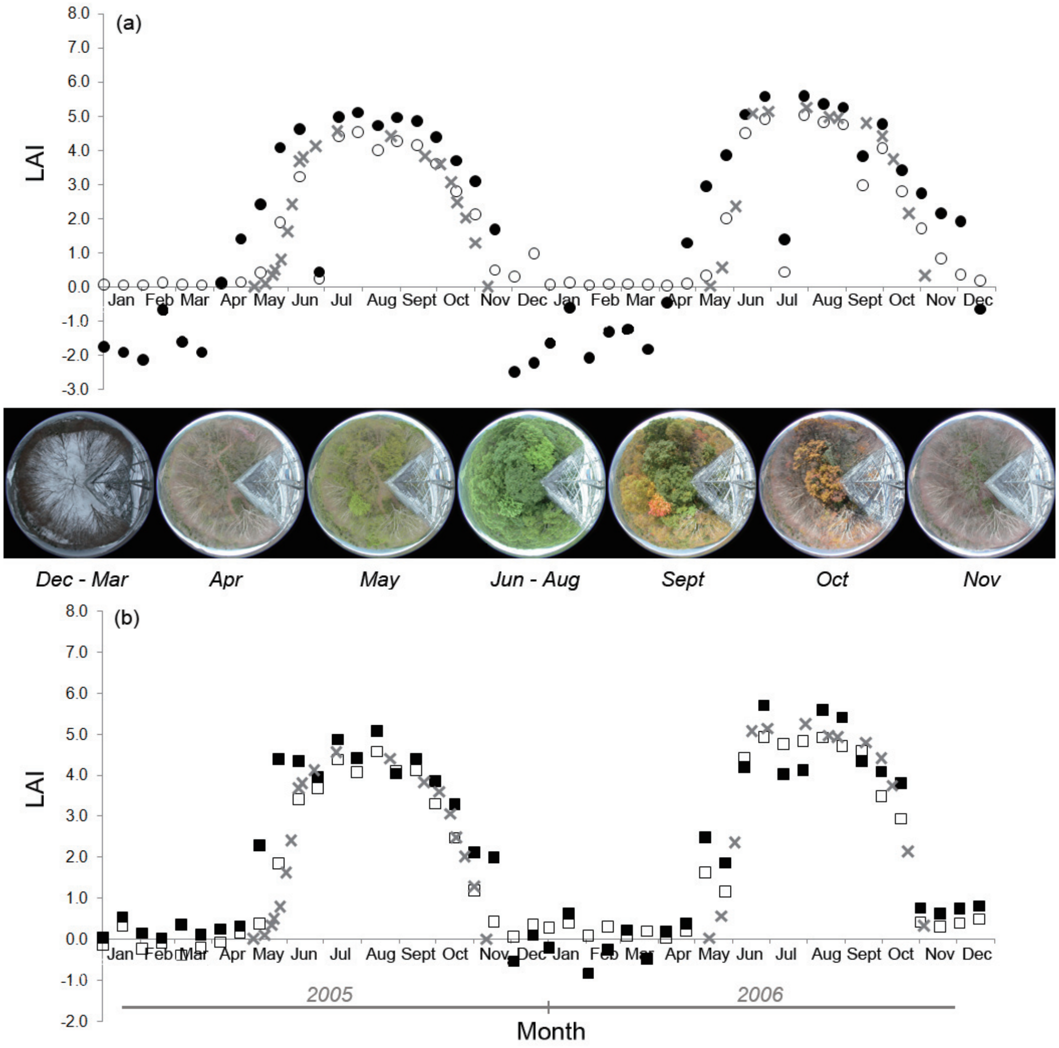

Figure 2. Time series of *in situ* LAI against estimated LAI based on (a) MODIS NDVI and (b) MODIS EVI. The signs of cross, open signs and solid sing are *in situ* LAI, LAI based single relationship and LAI based double relationships, respectively, from 2005-2006.

one line, with an r^2 value of 0.88. Furthermore, $NDVI_{MODIS}$ yielded seasonally earlier LAI values than did *in situ* LAI estimates, as it included the forest floor. The double relationships results were improved, with LAI estimates similar to those of *in situ* LAI. The overestimation error of linear relationship $NDVI_{MODIS}$ was reduced, and forest floor reflectance in the early growing season was decreased, thus fitting better to *in situ* LAI values than EVI_{MODIS}. The fluctuation of both $NDVI_{MODIS}$ and EVI_{MODIS} winter LAI estimates derived from the single relationship was considerably removed, and both were close to reflecting the actual leafless condition of winter.

From the results in the figure 2, the LAI value based single relationship overestimated comparing with *in situ* LAI. Whereas the double relationships provide the best fit relationship for each period, and the LAI-VI relationship is not exactly a linear relationship (Myneni et al., 2002). Thus, the single relationship does not accurately estimate results. Kume et al. (2010) stated that NDVI responded to the different reflectance characteristics of the leaves that may affect to LAI. However, for EVI, the difference between the single and double relationships was not large as NDVI.

Therefore, we suggest that the double relationships are better

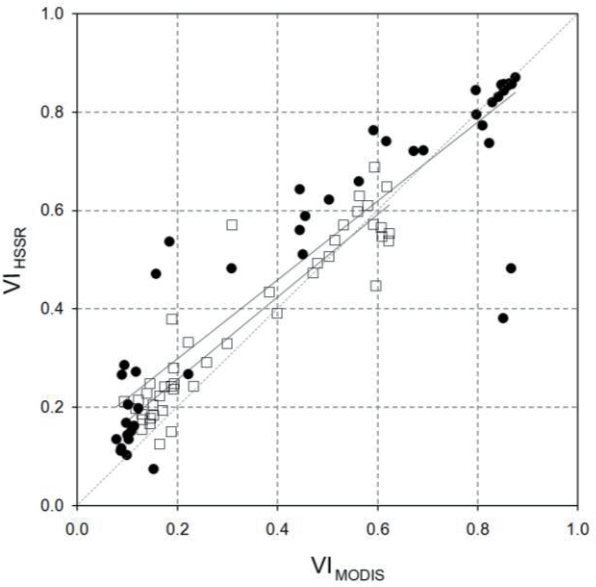

Figure 3. Comparison between *in situ* NDVI (solid circle) and EVI (open rectangular) from hemispherical spectroradiometer with NDVI and EVI from MODIS (solid circle).

the leaf phonological cycle of the deciduous broadleaf forest. It can improve the LAI estimations by reducing the errors of overestimation.

Moreover, *in situ* LAI values were plotted against $\mathrm{LAI}_{\mathrm{MODIS}}$ values in Figure 4. $\mathrm{LAI}_{\mathrm{MODIS}}$ presented higher values then *in situ* LAI. Myneni et al. (2002) also compared $\mathrm{LAI}_{\mathrm{MODIS}}$ products and *in situ* LAI and found similar overvaluations of $\mathrm{LAI}_{\mathrm{MODIS}}$ in deciduous broadleaf forests.

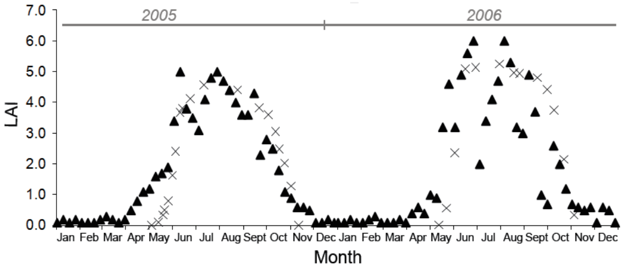

Figure 4. Time series of *in situ* LAI against MODIS LAI. The signs of cross and solid triangular are *in situ* LAI and MODIS LAI from 2005-2006.

4. CONCLUSIONS

The LAI-NDVI and LAI-EVI relationships were investigated based on in situ data, since it provided the reliable, long-term and no effects data from the cloud and atmosphere. NDVI and EVI were calculated from spectral reflectance observed by spectroradiometer. LAI was measured by the phonological shoot and litter trap approaches. The obtained relationships were validated against MODIS NDVI and EVI data. The results were concluded as (1) NDVI and EVI can show the seasonal variations of LAI, but it presents the value earlier than *in situ* LAI value started due to the effects of forest floor, (2) for the single relationship, NDVI and EVI had the linear relationship with in situ LAI, and (3) the different patterns between LAI and VI were clearly illustrated in the double relationship, then it can improve the LAI estimations better than the single relationship. These results suggested that the LAI-VI relationship in the leaf expansion to saturation period should be considered when LAI means the green leaf area that directly affecting to the photosynthesis process for estimating the primary production.

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