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Onset Date of Forest Canopy Detected from MODIS Leaf Area Index

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ABSTRACT: The timing of the canopy phenology onset (CPO hereafter) indicates the initiation of the growing season, with rapid increases in exchange rates of carbon dioxide and water vapor between vegetation and atmosphere. The CPO is regarded as a potential indicator of ecosystem responses to global warming, but the CPO shows considerable spatial variation depending on the species composition and local temperature regime at a given geographic location. In this study, we evaluated the utility of satellite observation data for detection of the timing of the CPO. Leaf area indices (LAI) obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) were utilized to detect and map the onset dates from 2001 to 2006. The reliability of MODIS-based onset dates was evaluated with ground measured cherry blossom flowering data from national weather stations. The MODIS onset dates preceded the observed flowering dates by 8 days and were linearly related with a correlation coefficient of 0.58 ($p < 0.05$). In spite of the coarse spatial (1 km) and temporal (8 days) resolutions of MODIS LAI, the MODIS-based onset dates showed reasonable ability to predict flowering dates.

Key words: Canopy phenology onset (CPO), Flowering date, Leaf area index, MODIS

INTRODUCTION

Vegetation phenology is an important component of spatial and temporal exchanges in terrestrial carbon, water, and energy cycles. The timing of onset and offset of vegetation is particularly important, as it is closely related with photosynthesis (Kimball et al. 1999, White et al. 1997, Myneni et al. 1997). Understanding spatial and annual patterns of CPO is essential for diagnosis of the current status of forest biomes, and prediction of their future responses to global climate change. However, phenological field observations are available only for limited locations and cannot cover the whole gradient of environmental conditions occurring across a wide geographic area. In Korea, the spatial variation in environmental factors affecting the CPO is quite large due to the spatial heterogeneity resulting from the complex land cover and rugged topography. Hence, it is difficult to extrapolate onset observations from a limited set of locations to other areas.

In recent years, remote sensing data has been used for phenological research, because of its potential for collection of data from a regional to a global scale (e.g., Myneni et al. 1997). For example, the Normalized Difference Vegetation Index (NDVI) from Advanced Very High Resolution Radiometer (AVHRR) data has been used to determine phenological event dates (Zhang et al. 2003). Compared with previous satellite sensors (e.g. AVHRR), the Moderate Resolution Imaging Spectoradiometer (MODIS) sensors on the Terra and Aqua satellites from NASA's Earth Observing System provide enhanced land surface reflectance data using 36 spectral bands. Zang et al. (2003) attempted to detect phenological events of vegetation using the MODIS EVI product. They concluded that remotely sensed data can be used to estimate phenological event dates together with a land cover map. Kang et al. (2003) used the MODIS LAI product to detect CPO dates at 77 national weather stations in Korea and developed a regional-scale onset model.

Field CPO data collected from wide range of different species, climatic regimes and geographic locations is required to evaluate the reliability of satellite-derived CPO dates. In Korea, field CPO observations are now being obtained from several forested areas under long-term ecological research frameworks, but the data are from a limited number of locations and are limited in duration. The Korea Meteorological Administration (KAM) also collects field data of flowering dates for several shrub and overstory species at 77 National Weather Stations (NWS). The first observations were collected in 1921 at four sites. Although it is difficult to find direct and robust evidence about the relationship between the flowering date and the CPO date of tree species, there is abundant indirect evidence that these dates are closed related. For example, Kim and Yoo (1985) found that flowering and leaf onset dates of *Rhododendron mucronulatum* and *R. schlippenbachii* at the same elevation were linearly related. Min and Choi (1993) suggested that both budding and flowering times of several woody species were related to local temperatures. Similarly, Jung et al. (2005) and Kwon et al.

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(2005) reported a close relationship between cherry flowering and bud burst of Korean grapevines and temperature regimes. Close relationships between both flowering and CPO dates and air temperatures have also been reported from many other geographic regions (Cesaraccio et al. 2004, De Melo-Abreu et al. 2004). The indirect evidence suggests that woody plant flowering data (e.g., cherry blossom flowering dates) can be utilized as a surrogate for CPO dates of woody plant species. Therefore, while CPO dates are not known from across Korea, we have sufficient flowering date for an indirect evaluation of satellite-derived CPO dates.

In this study, we attempted to improve a method suggested by Kang et al. (2003) for mapping the CPO of forest biomes in Korea using MODIS 8-day LAI data. The major changes to the existing method were (1) we developed a more objective and enhanced smoothing process of MODIS LAI relative to those suggested by Kang et al. (2003) and (2) we evaluated the reliability of the MODIS-based CPO using the more extensive database of national cherry blossom flowering dates from 77 national weather stations (NWS) from 2001 to 2006. After testing the algorithm with the flowering data, we then produced MODIS-based onset maps to demonstrate spatial and annual variation in onset dates from 2001 to 2006.

MATERIALS AND METHOD

Collection of Satellite and Field Observation Data

MODIS Data

In this study, we compiled MODIS landcover maps (type 1 IGBP, International Geosphere Biosphere Programme) product (MOD12Q1) and 8-day composite MODIS LAI and FparLAI_QC (Quality control flag) product (MOD15A2, collection 4) from 2001 to 2006 using the Earth Observing System data gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). The maps have 1 km spatial resolution. There were two missing weeks for MODIS LAI and QC (June 18 and 26, 2001). We filled in the missing data with values from the previous (June 10) and the next (July 4, 2001) week's images.

MODIS LAI products estimate LAI on a daily basis and then combine the daily LAI to provide the 8-day LAI product (MOD 15A2). The 8-day composite LAI represents the maximum LAI for 8-day period, and is designed to reduce undesirable effects from cloud or snow cover. The associated FparLAI_QC flags from MOD 15A2 include information on LAI quality as well as cloud state. In this study, the QC flags were used to remove bad pixels caused by clouds, rainfall or other geometry problems. The QC flags representing good data are decimally 0, 1, 33, 96, and 97 (Myneni et al. 2003). We used a landcover map of year 2004 since the map showed the best agreement among the maps from 2001 to 2006 with a higher-resolution landcover map from the Ministry of Environment. In this preliminary analysis of the Bukhan river basin, the two maps showed >90% agreement for the forest biome although the level of agreement for evergreen needleleaf forest, deciduous broadleaf forest, and mixed forest was much less than that for the entire forest biome (not shown in this paper).

Field Phenology Data: Cherry Blossom Flowering Date

Plant phenology field data were collected from the Korea Meteorological Administration (KMA). These data include the beginning of formation, burst, and full bloom dates of several plant species at 77 national weather stations from 1921 to 2006. We used cherry blossom flowering data to evaluate MODIS-based CPO from 2001 to 2006 since the cherry blossom is an overstory species, flowering occurs in the upper parts of the crown, and the beginning of cherry blossom flowering is related to the beginning of the growing period of crops, occurring several days earlier than CPO dates in forest biomes in the temperate zones. In this evaluation, it was assumed that cherry blossom flowering occurs several days earlier but is linearly related with the CPO of forest biomes.

The spatial resolution (1 km) of MODIS landcover and LAI is too coarse to delineate the leaf burst or flowering of individual trees. Within a MODIS pixel, considerable spatial heterogeneity could exist due to complex landcover or rugged topography. Hence, we screeened the 77 NWS prior to including their data in our evaluation of MODIS onset dates. Sites were selected based on two criteria: 1) landcover heterogeneity and 2) landcover and topographic complexity.

We included NWS sites in which: (1) The area within the 5 × 5 window pixels (25 km^2) included more than 30 percent (8 pixels) forest (deciduous broadleaf and mixed forest) biomes. This criterion was designed to ensure that forest is not minor biome type around the NWS site. (2) The standard deviations of landcover and elevation in the 5 × 5 window pixels (25 km^2) were collectively less than specified values. This criterion was designed to exclude NWS sites in which the landcover is too heterogeneous or the local topography is complex.

After the first criterion was applied, only 19 NWS sites remained to be used for deriving time series of MODIS LAI. After the second criterion was applied, five more NWS sites were excluded from the final analysis. Details of the second screening process are described in the Results.

DATA Manipulation

Smoothing Process for LAI Time-series

For MODIS onset detection, 5 × 5 pixels (25 km^2) around the

NWS were cut out by locating each NWS at center of the window. Within the 5 × 5 windows, we considered only pixels of deciduous broadleaf forest and mixed forest for onset detection. The original time-series of MODIS LAI showed inconsistencies, with big drops during summertime, which were mainly due to cloud contamination (Kang et al. 2005). Therefore, before detecting onset dates, we modified the data to reflect more reasonable patterns of seasonal LAI, that is, gradually increasing from early spring, reaching maximum in early summer, and then decreasing from early autumn. For this, we carried out a 4-step smoothing processes as follows.

(1) Quality control flags were applied to forest pixels of 5 × 5 pixels to remove bad values due to the presence of cloud or other geometry problems (Fig. 1a). (2) If an LAI pixel was discarded due to a bad QC flag, we applied spatial interpolation. Neighboring pixels within 5 × 5 windows with a forest biome type and a good QC flag were used to fill the discarded LAI pixel. If spatial interpolation failed, temporal interpolation using the data from the previous week was applied (Fig. 1b). (3) Further modification was applied to make the LAI monotonically increase during the presumed growing period (DOY 73 - 201) and then decrease during the presumed offset period (DOY 257 - 365). Decreasing patterns in the eonset period and increasing patterns in the offset period were corrected (Fig. 1c). After this correction, weeks with the maximum increase (LAI_{maxdif}) and decrease (LAI_{mindif}) of LAI were found for the next modification. As a final step, (4) monotonic backward and forward decreasing patterns from LAI_{maxdif} and LAI_{mindif} were assumed for onset and offset periods, respectively (Fig. 1d).

Onset Detection

After the stepwise modifications of the LAI timeseries, we applied the threshold method of Kang *et al.* (2003) to detect onset dates from the MODIS LAI product. This method converts LAI to normalized LAI (0-1) during the onset period to remove the effects of evergreen vegetation and assumes that onset occurs when the normalized LAI exceeds a certain threshold value ($LAI_{n,C}$). In this study, the onset period was presumed to occur from seven weeks before to five weeks after the week of LAI_{maxdif}. Eq(1) was used

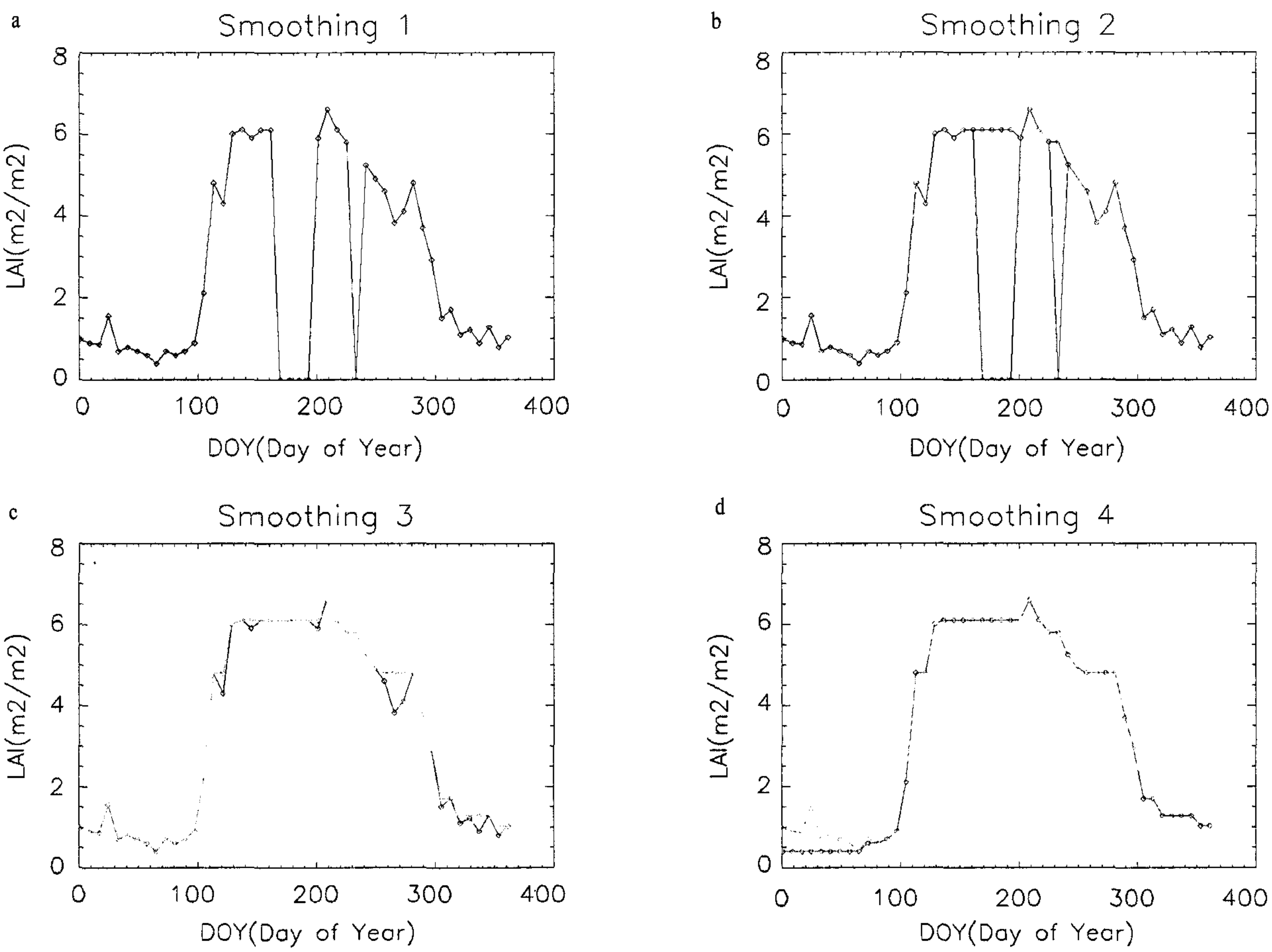


Fig. 1. Smoothing process for LAI time series. (For details, see 2.2.1)

to normalize LAI for the onset period.

$$LAI_{n,i} = \frac{LAI_{M,i} - LAI_{M,\min,i}}{LAI_{M,\max,i} - LAI_{M,\min,i}} \quad (1)$$

Where $LAI_{n,i}$ is the output of the normalized LAI for i th site, ranging from 0 to 1. $LAI_{M,\max,i}$ and $LAI_{M,\max,i}$ are the maximum and minimum LAI for i th site within the onset period, respectively. $LAI_{M,i}$ is 8-day MODIS LAI.

We applied five threshold values ($LAI_{n,C}$) ranging from 0.1 to 0.3 with 0.05 intervals. The onset week was detected for each threshold and then onset dates were interpolated using linear interpolation as suggested by Kang et al. (2003). The MODIS-based onset dates were compared with actual cherry blossom flowering dates from the selected NWS. Finally, we applied the algorithm for mapping onset dates for deciduous broadleaf and mixed forest in Korea from 2001 to 2006.

RESULTS

Retrieved MODIS LAI

The nineteen NWS sites selected using the first site screening criterion and their seasonal LAI are shown in Fig. 2. The dashed and solid lines in Fig. 2 show the seasonal LAI patterns after the first step and the fourth step of the smoothing process for the selected 19 NWS sites for year 2005. Compared with the seasonal LAI patterns after only a one-step smoothing process, the patterns were much more reliable after all four smoothing steps. Big drops in LAI are still found at some sites (e.g. Inje) in the period between DOY 201 and 257 because smoothing was not applied for that period.

From the LAI seasonal patterns, it seems that timing of LAI increase is quite variable from DOY 90 at Namhae to 120 Daegwallyeong. In spite of the use of four smoothing processes, however, some sites still displayed strange patterns. For examples, Sungsanpo did not show a clear seasonal pattern and the high LAI at Chupungnyeong from June to September was not well coordinated with the relatively low LAI in springtime. In addition, the LAI increased in late winter or early spring at some low-latitude NWS sites (e.g. Geoje, Namhae, Wando, Sungsanpo), an effect that might be caused by winter crops. Though only NWS sites with >30% forest cover within 25 km^2 were selected, it seems that the LAI values were still affected by sub-pixel land cover heterogeneity or topographic gradients of onset timing. Accordingly, the NWS sites

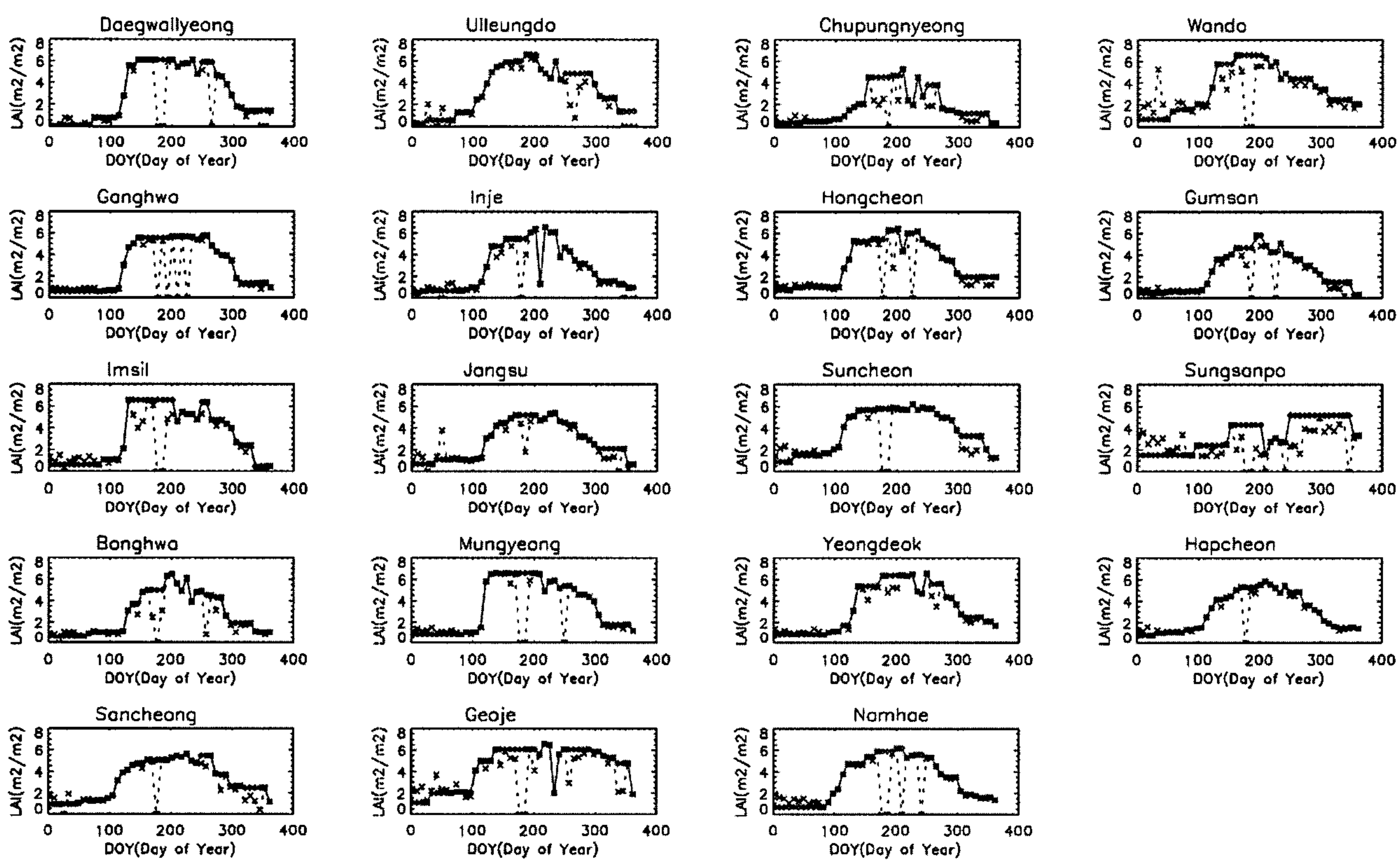


Fig. 2. Derived LAI time-series for study sites. The dotted and solid lines represent seasonal LAI patterns after the first step and the fourth step, respectively, of the smoothing process for the selected 19 NWS sites for year 2005.

were subjected to the second site screening process.

Detection of Onset Dates

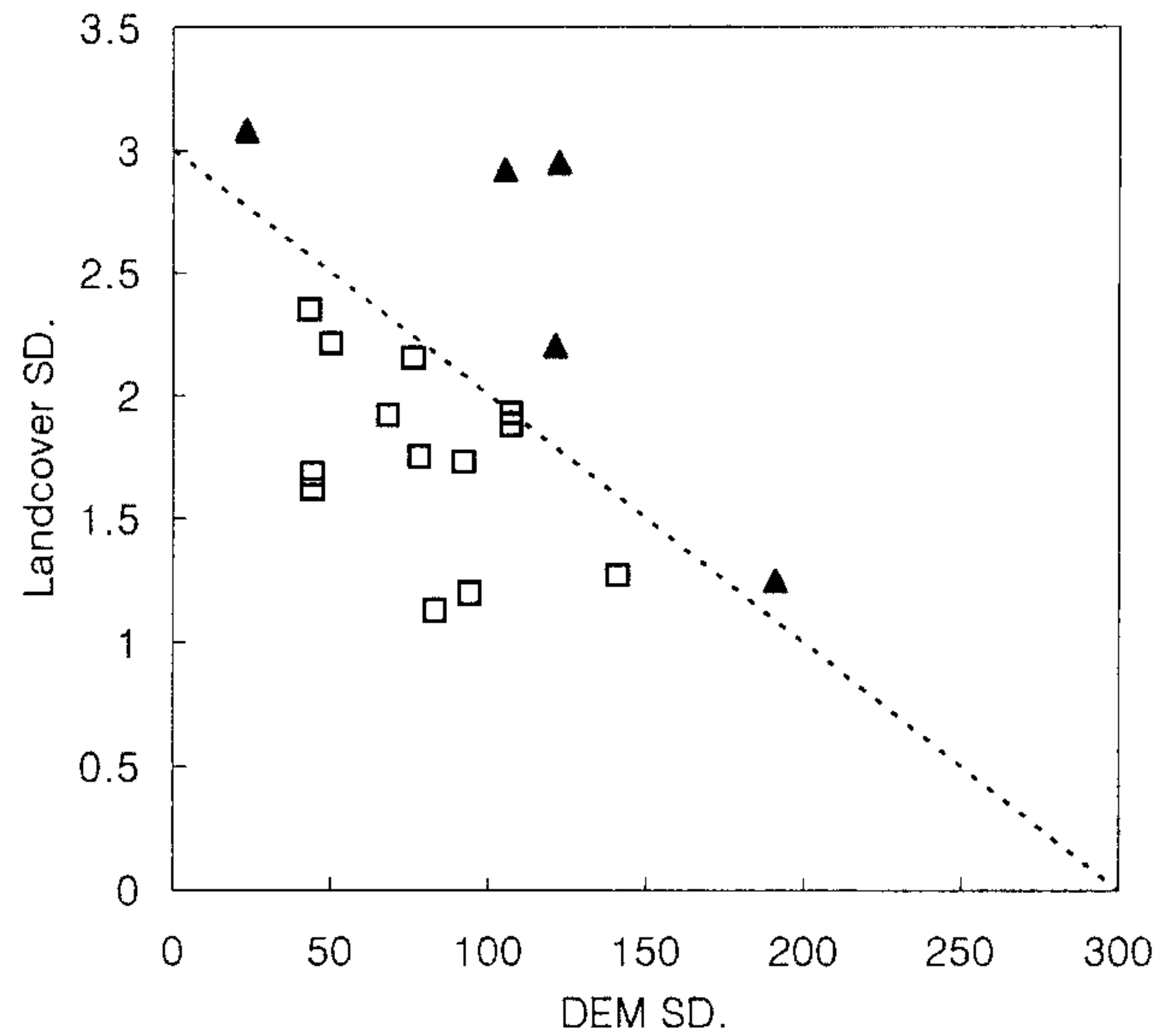
MODIS-derived onset dates at the 19 NWS sites ranged from DOY 21 to 133 depending on the threshold applied ($LAI_{n,C}$). Generally, MODIS-derived onset dates preceded the cherry blossom flowering dates, except when the threshold value of 0.1 was applied (Table 1). The linear relationship between MODIS onset and flowering dates was highest at the threshold value of 0.15. The MODIS onset explained 29% of the variation in flowering dates (Table 1) and the mean error (ME) and root mean squared error (RMSE) were 5.8 and 15.3 days.

The second site screening process was applied to discard sites with considerable heterogeneity of land cover and topography. We plotted the standard deviations of landcover and altitude against each other and discarded sites with high standard deviations for either landcover, altitude, or both. That is, sites over the dotted line in Fig. 3(a). This process excluded five sites (Daegwallyeong, Wando, Sungsanpo, Geoje, and Namhae) from further evaluation. After the second site screening, the threshold value of 0.15 still performed the best and both linearity ($R^2 = 0.34$) and RMSE (11.4 days) increased. Fig. 3(b) shows scatter plots before and after the second site screening process. Open circles in Fig. 3(b) indicate data from the five sites that were excluded. The second site screening step removed some of major uncertainties in the MODIS onset dates but the considerably earlier detection of MODIS onset still needs to be explained in future study.

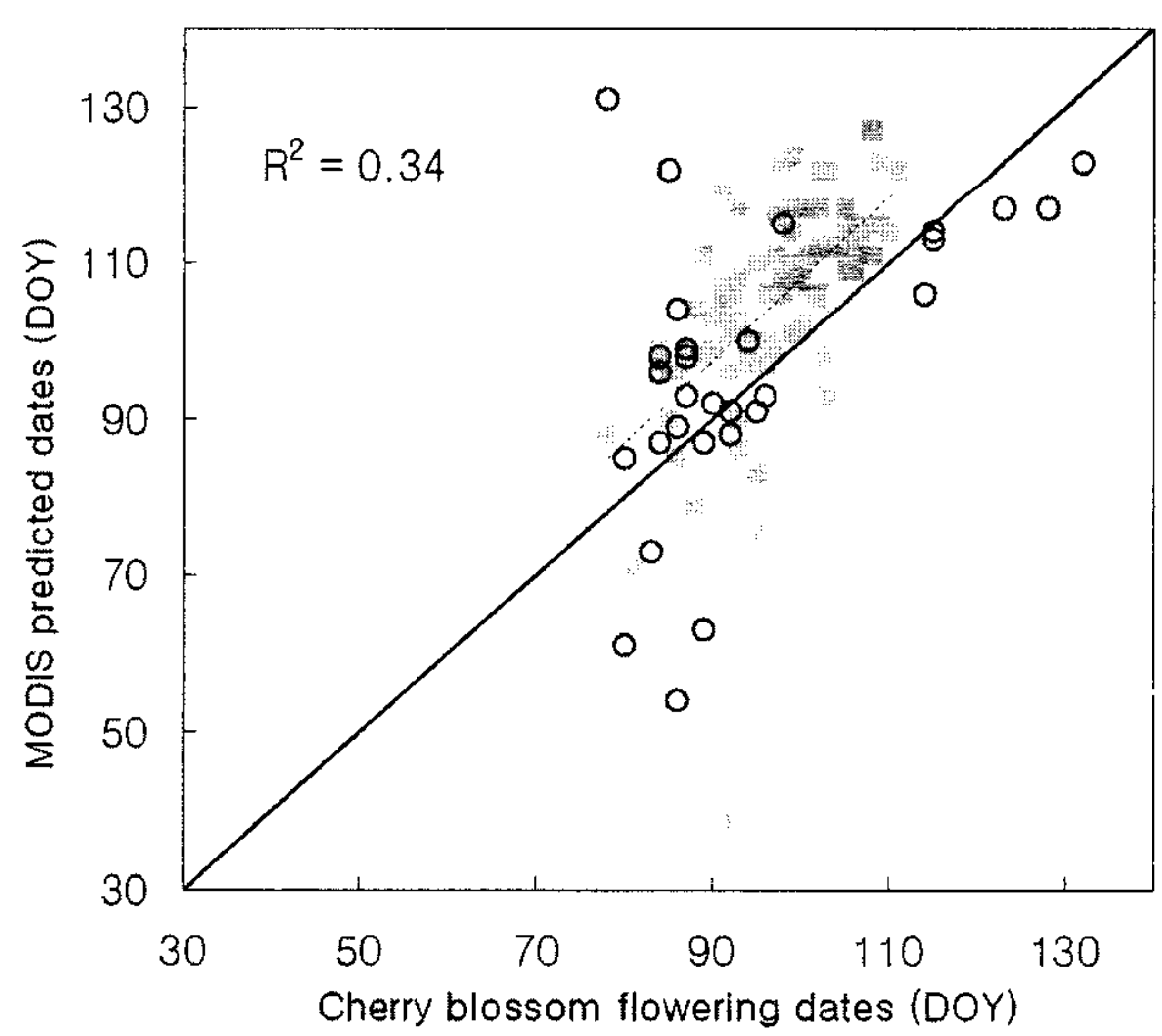
Table 1. Statistical analysis comparing MODIS predicted onset and cherry blossom flowering dates with varying threshold ($LAI_{n,C}$)

(a) For 19 NWS sites					
	$LAI_{n,C}$				
	0.1	0.15	0.2	0.25	0.3
R^2	0.21	0.29	0.23	0.23	0.24
RMSE (days)	15.8	15.3	17.4	18.0	19.0
ME (days)	−0.8	5.8	9.4	12.1	14.5
(b) For 14 NWS sites after the second site screening process					
	$LAI_{n,C}$				
	0.1	0.15	0.2	0.25	0.3
R^2	0.27	0.34	0.23	0.25	0.24
RMSE (days)	10.8	11.4	13.8	14.6	16.3
ME (days)	1.7	7.8	11.5	14.0	16.2

R^2 = coefficient of determination.
RMSE = root mean square error.
ME = mean error.



(a)



(b)

Fig. 3. Site selection and comparison of onset and flowering dates: (a) We plotted the standard deviations of landcover and altitude against each other, and discarded sites with high standard deviations for either variable. That is, sites over the dotted line. Five sites (Daegwallyeong, Wando, Sungsanpo, Geoje, and Namhae) were excluded; (b) Scatter plot of the observed cherry blossom flowering dates and MODIS predicted CPO dates ($LAI_{n,C}$ =0.15). Yellow squares represent the 13 NWS sites after the second site screening process and open blue circles represent the 5 NWS sites excluded. R^2 was calculated only for the yellow squares. DOY is days of year.

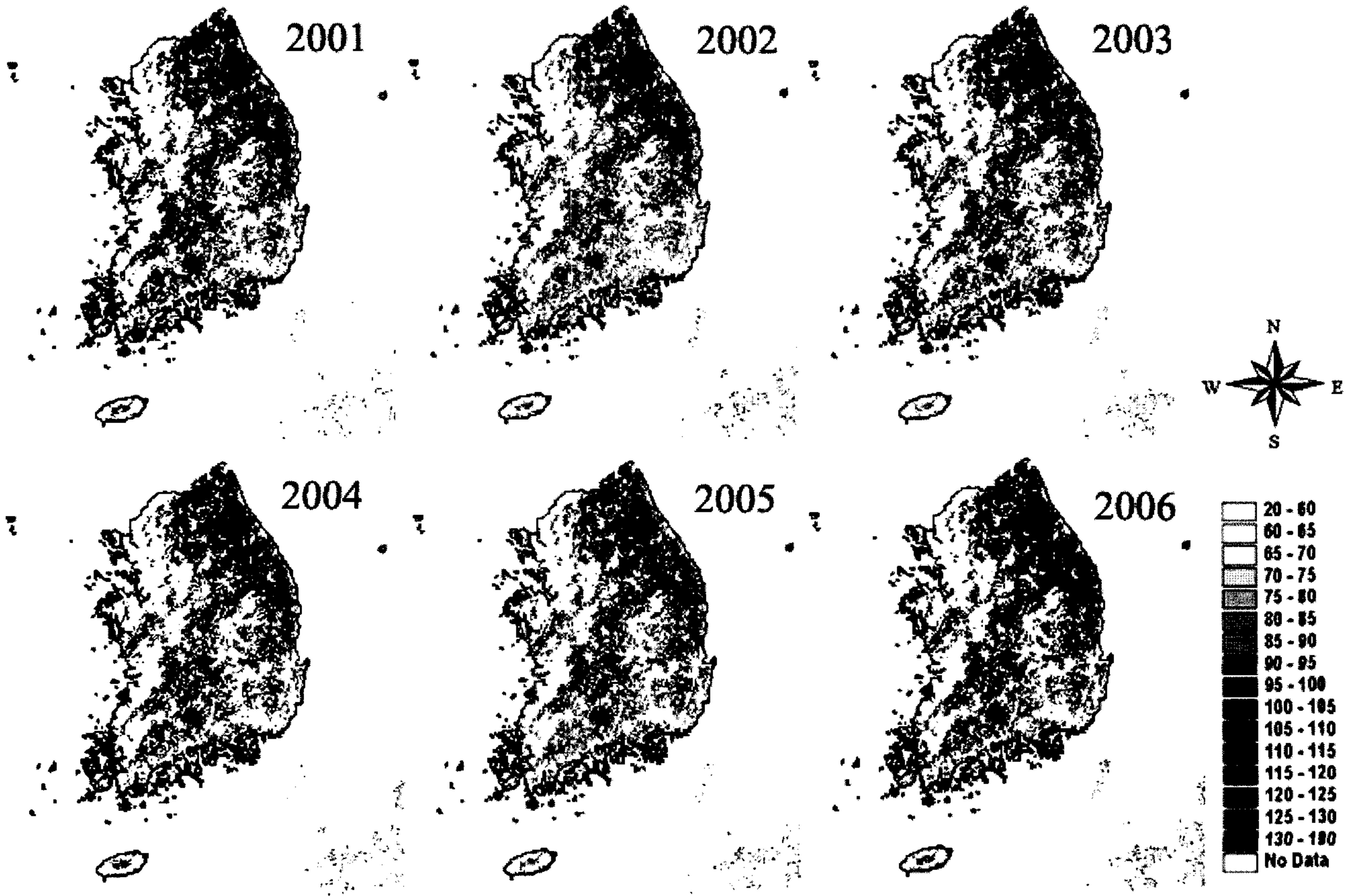


Fig. 4. MODIS predicted onset maps from 2001 to 2006 with threshold value of 0.15.

Based on the results, onset mapping was conducted by applying stepwise modification processes on LAI seasonal patterns with the threshold value of 0.15. This produced maps showing the gradients of onset dates with latitude and altitude (Fig. 4). The onsets start in the south and at low elevations and gradually spread northward and to higher elevations, which is reasonable given the climatic gradients of latitude and altitude involved. Fig. 4 also shows considerable annual variation in onset dates. The mean onset dates on the map ranged from DOY 100 in 2002 to 112 in 2006 with DOY generally increasing over time: 100 (year 2002), 102 (2004), 103 (2003), 104 (2001), 106 (2005) and 112 (2006), respectively.

DISCUSSION AND CONCLUSION

CPO data is useful for monitoring responses of vegetation to climate change and is essential for many ecosystem models simulating vegetation growth and exchange rates of carbon and water fluxes between the land surface and the atmosphere (Cesaraccio et al. 2004, De Melo-Abreu et al. 2004, Jung et al. 2005, Kwon et al. 2005). We suggested a method for detecting onset dates from the MODIS LAI product and demonstrated its applicability by comparing MODIS onset dates with cherry blossom flowering field data. Our results fall within a reasonable range and the method was efficient in generating maps for onset dates in Korea but this study was still constrained by several limitations including: (1) problems with the field data, including differences in the cherry tree species monitored, site characteristics, and specific criteria for detecting cherry blossom flowering at each NWS site, and (2) limitations of the MODIS data, including subpixel heterogeneity within a LAI pixel and utilization of the 8-day maximum composite of LAI.

The MODIS-based onset dates were generally later than the observed cherry blossom flowering dates but the timing of onset dates varied considerably depending on the threshold value applied in this study. Hence, the threshold value is a key variable for more rigorous parameterization using field data. Considering that cherry blossom flowering data already provides only indirect information about CPO, additional direct validation with actual field CPO data is still required.

In this study, a 5×5 moving window method was applied to mitigate the effects of clouds on seasonal LAI. Though the moving window is efficient in reducing cloud contamination of LAI product, it can provide the undesirable side effect of reducing spatial resolution. After spatial interpolation was applied using 5 × 5 window pixels, the spatial resolution of LAI is not necessarily 1 km any more. Though this is not a serious problem in relatively flat and homogeneously forested areas, it could create considerable uncertainty in Korea, which has a rugged topography and heterogeneous land cover. In future study, it will be necessary to develop enhanced methods to retain high spatial resolution while removing the effects of cloud contamination. Similarly, the methods for selection of NWS sites for model validation should be improved in future studies.

In spite of these limitations, our approach demonstrates the usefulness of the MODIS 8-day LAI product and our objective stepwise smoothing process for detecting onset of greening of vegetation. Detecting phenological events (i.e., onset and offset) of vegetation from satellite images will provide a useful tool for monitoring ecosystem changes and improving the accuracy of ecosystem models simulating ecosystem carbon and water budgets.

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