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Monitoring spring canopy phenology of a deciduous broadleaf forest using MODIS

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Abstract

Climate change is predicted to alter the canopy phenology of temperate and boreal forests, which will affect carbon, water, and energy budgets. Therefore, there is a great need to evaluate remotely sensed products for their potential to accurately capture canopy dynamics. The objective of this study was to compare several products derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) to field measurements of fraction photosynthetically active radiation (FPAR) and plant area index (PAI) for a deciduous broadleaf forest in northern Wisconsin in 2002. MODIS products captured the general phenological development of the canopy although MODIS products overestimated the leaf area during the overstory leaf out period. Field data suggest that the period from budburst to canopy maturity, or maximum PAI, occurred in 10 to 12 days while MODIS products predicted onset of greenness and maturity from 1 to 21 days and 0 to 19 days earlier than that from field observations, respectively. Temporal compositing of MODIS data and understory development are likely key factors explaining differences with field data. Maximum PAI estimates differed only by 7% between field derived and MODIS-based estimates of LAI. Implications for ecosystem modeling of carbon and water exchange and future research needs are discussed.

Keywords: Understory vegetation; Plant area index; Leaf area index; Photosynthetically active radiation; NDVI

1. Introduction

Assessment of vegetation phenology using remotely sensed data has a long history (Ashley et al., 1973; Girard, 1982; Rea & Ashley, 1976; Rouse et al., 1973; Sayn-Wittgenstein, 1961) with more recent studies making use of satellite data to examine the potential effects of climate change on phenology (e.g., Myneni et al., 1997; White et al., 1997; Zhang et al., 2004). Vegetation phenology, as used and studied with remote sensing related research, refers to the relationship between climate and periodic development of photosynthetic biomass. Accurate estimates of canopy phenology are critical to quantifying carbon and water exchange between forests and the atmosphere and its response to climate change.

Satellite monitoring of vegetation phenology has often made use of a vegetation index such as NDVI because it is related to the amount of green leaf biomass (Lillesand & Keifer, 2000). Annual time series NDVI data from AVHRR, for example, have been used to estimate the onset of leaf development and senescence in relation to interannual variations in average global air temperature for the past twenty years (Myneni et al., 1997; Shabanov et al., 2002; Tucker et al., 2001; Zhou et al., 2001). Recent efforts have focused on improved methods for calculating specific dates of vegetation phenological transitions using improved satellite data products (e.g., MODIS–EVI/LAI) and modeling techniques (Kang et al., 2003; White et al., 1997, 2002; Zhang et al., 2003). The vegetation products generated from MODIS onboard Terra and Aqua offer an unprecedented opportunity for researchers to develop long-term records of vegetation phenology at spatial scales as small as 250 m. Still, as White and Nemani (2003) point out, there exists potential confusion and bias on how to calculate phenological transition times due to the mix of methods and definitions being used.

The biophysical and radiometric principles of using a satellite-based vegetation index or related measures (e.g., leaf area index)

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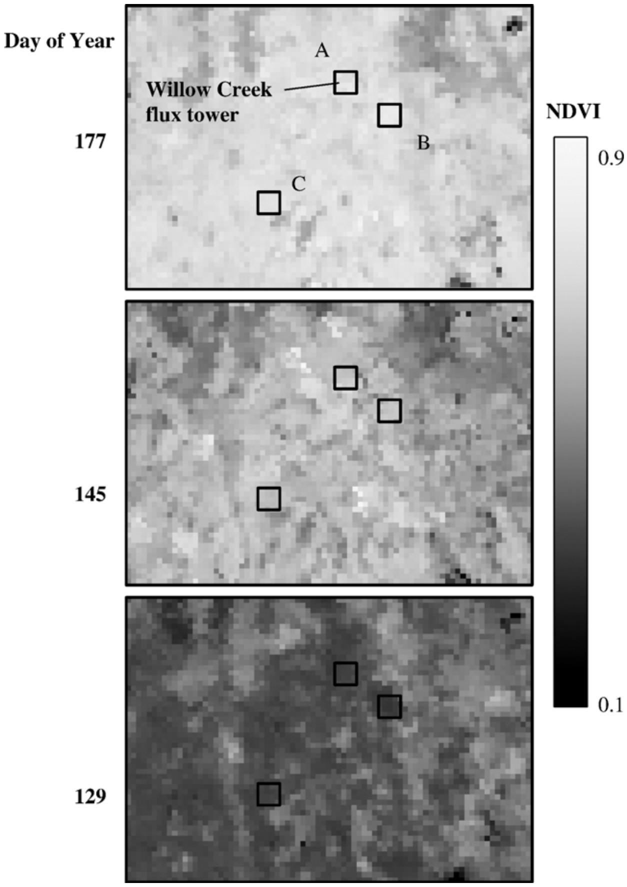

Fig. 1. Area for measurement locations superimposed on three dates of the MOD13Q1 250 m NDVI product. Center coordinates for each site: Site A = 90°04′31.8″W, 45°48′21.1″N; Site B = 90°02′56.5″W, 45°47′33.7″N; Site C = 90°06′54.8″W, 45°45′05.8″N.

to detect vegetation phenology, in general, are well established (Huete et al., 2002; Rea & Ashley, 1976; Rouse et al., 1973; Shabanov et al., 2002, 2003; Tian et al., 2002; Tucker, 1979; Yang et al., in press-a,b). However, much less is known about the temporal sensitivity needed to detect phenological transitions from field measurements or satellite-based vegetation products. Cowling and Field (2003) examined the sensitivity of LAI to plant resource availability, including CO_2, and suggested the links among LAI, canopy development, and primary production used in most ecosystem models to examine the effects of climate change required further study. Zhang et al. (2004) used time series EVI to estimate phenological transition times from a curvature rate-of-change function coupled with MODIS land surface temperature data. They concluded there is a great need to couple field measurements and reflectance data to understand how species level responses to climate effects may influence large scale studies, especially using satellite data with pixels containing mixed species. Schwartz et al. (2002) compared three methods using satellite data for determining the onset of greenness of a deciduous broadleaf stand at the Harvard forest in Massachusetts and concluded that each does reasonably well when compared to field measurements of budburst data.

The overall objective of this research was to quantify and compare field measurements of springtime forest canopy phenology onset and maturity to estimates calculated from MODIS-derived vegetation products. We focused on a deciduous broadleaf forest in northern Wisconsin for two reasons: (i) to minimize mixed species effects and (ii) deciduous canopies ensured the greatest change in spring canopy reflectance. The specific objectives of this study were to: 1) determine how well field measurements of PAI and FPAR can accurately quantify canopy phenology transitions identified in Zhang et al. (2003), 2) assess phenology transition estimated from MODIS products, and 3) examine the effects of temporal aggregation on determining onset dates.

2. Methodology

2.1. Study area

The study area was located near an above-canopy flux tower, near Willow Creek in northern Wisconsin (Bolstad et al., 2004). The topography is slightly rolling with a maximum elevation difference of approximately 20 m. The climate is cool, temperate continental, with mean air temperatures ranging from −12 °C to 19 °C for January and July, respectively. Average precipitation is 811 mm/year for this region (Barish & Meloy, 2000). We established three independent study sites (Fig. 1) dominated by sugar maple (*Acer saccharum* Marsh.) with some basswood (*Tilia americana* L.) and green ash (*Fraxinus pennsylvanica* Marsh.) throughout. All stands were approximately 66 to 87 years old and occurred on a predominately sandy loam soil texture.

A sampling grid was established at each site based on Burrows et al. (2002) with the potential of up to 36 plots per site.

Table 1
MODIS data products used in this study and their characteristics as obtained from the EOS Data gateway

MODIS Product	Spatial resolution	Description	References
MOD09GQK	250 m	Daily surface reflectance computed from MODIS bands 1 (620–670 nm) and 2 (841–876 nm).	Vermote et al., 1997
MOD13Q1 NDVI	250 m	Normalized difference vegetation index (NDVI) computed from MOD09GQK and composited from 16 days of data.	Huete et al., 2002
MOD13Q1 EVI	250 m	Enhanced vegetation index (EVI) computed from MOD09GQK and composited from 16 days of data.	Huete et al., 2002
MOD15A2 LAI	1000 m	Leaf area index (LAI, one sided) computed from 1 km surface reflectance and land cover definition using radiative transfer or empirical (backup) methods, 8 day composite.	Yang et al., in press-a,b
MOD15A2 FPAR	1000 m	Fraction of photosythetically active radiation (FPAR) absorbed by the vegetation computed from 1 km surface reflectance and land cover definition using radiative transfer or empirical (backup) methods, 8 day composite.	Yang et al., in press-b
MOD43B4	1000 m	Nadir BRDF-adjusted reflectance composited from 16 days of data.	Schaaf et al., 2002

Table 2
Plant area index (PAI) and fraction intercepted photosynthetically active radiation (FIPAR) for each date collected with the LAI-2000 for the three sites

	Site A			Site B			Site C			Combined		
	PAI	FIPAR	*n*	PAI	FIPAR	*n*	PAI	FIPAR	*n*	PAI	FIPAR	*n*
May 27, 2002	1.72 (0.20)	0.69 (0.04)	16	1.74 (0.12)	0.70 (0.02)	20	1.65 (0.23)	0.68 (0.05)	38	1.69 (0.20)	0.69 (0.04)	74
June 1, 2002	3.74 (0.41)	0.92 (0.02)	48	3.93 (0.55)	0.92 (0.04)	24	3.94 (0.57)	0.93 (0.03)	43	3.86 (0.51)	0.93 (0.03)	116
June 7, 2002	4.41 (0.70)	0.95 (0.03)	12	4.02 (0.75)	0.94 (0.03)	20	3.77 (0.91)	0.91 (0.06)	16	4.05 (0.83)	0.94 (0.05)	48
June 28, 2002	5.71 (0.87)	0.98 (0.02)	18	5.94 (0.57)	0.98 (0.01)	18	5.38 (0.84)	0.98 (0.01)	10	5.73 (0.84)	0.98 (0.02)	46

Standard deviation in parentheses. Number of plots measured = *n*.

The first plot at each site corresponded to the upper northwest corner of a designated 540 m × 540 m area (Fig. 1). The plot grid within each area was a cyclic sampling design where the distances between plots in the east–west direction were 30, 60, 150, 120, and 180 meters. The cycle is repeated in the north–south direction for a complete grid of 6 × 6 plots. The design facilitated the calculation of spatial covariance and increased the efficiency of collecting field data (Burrows et al., 2002).

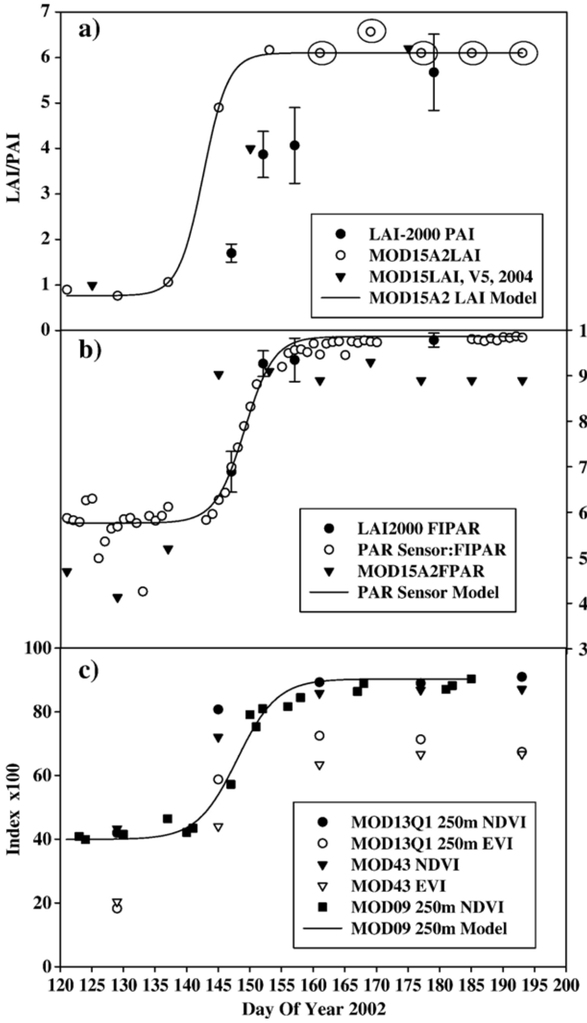

Fig. 2. Spring phenology of a deciduous broadleaf forest in northern Wisconsin: a) leaf area index (LAI) from MOD15A2 and plant area index (PAI) from LAI-2000. The circles around LAI values from MOD15A2 indicate LAI derived from the backup algorithm. Included for general comparison are three dates of LAI from MOD15 V005 in 2004 (Shabanov et al., 2005), b) Fraction photosynthetically active radiation absorbed (FPAR) and intercepted (FIPAR), and c) vegetation index from MODIS products. Error bars on FIPAR and PAI values represent standard deviation of combined LAI-2000 field data from three sites.

2.2. Field measurements

We measured fraction intercepted photosynthetically active radiation (FIPAR) and plant area index (PAI) using the LAI-2000 Plant Canopy Analyzer (LiCor Inc., Lincoln, NE) in each stand on four different dates in the spring of 2002. The sample dates spanned the complete spring canopy phenology (i.e., leaf expansion to maturity). However, due to logistical and time constraints with collecting LAI-2000 data under appropriate light conditions, we subsampled from the complete 6 × 6 plot design at each site. At each site, we measured FIPAR and PAI from a minimum of ten plots spanning the extent of the site (540 m) including one row and column of plots plus a diagonal segment.

The fraction of radiation intercepted by the canopy (both foliage and branches) for each plot was calculated as:

$$\mathrm{FIPAR} = 1.0 - \tau \tag{1}$$

where τ is the fraction of light transmitted by the canopy as determined from optical measurements with the LAI-2000. PAR was continuously measured at the Willow Creek flux tower (Site A) with separate PAR sensors above the canopy and at the bottom of the canopy.

2.3. MODIS data products

We compared several standard MODIS products with different spatial and temporal characteristics to our field data of

Table 3
Model determined onset of greenness and maturity (day of year) from each MODIS product

Sensor/product	Greenness onset	Greenness delta	Maturity onset	Maturity delta
PAR sensor	140		157	
MOD09 NDVI	139	−1	157	0
MOD13 NDVI	127	−13	153	−4
MOD13 EVI	128	−12	154	−3
MOD15 LAI	138	−2	148	−9
MOD15 FPAR	136	−4	138	−19
MOD43 NDVI	119	−21	161	4
MOD43 EVI	127	−13	162	5

Delta is the difference in number of days of each MODIS product prediction from the PAR sensor.

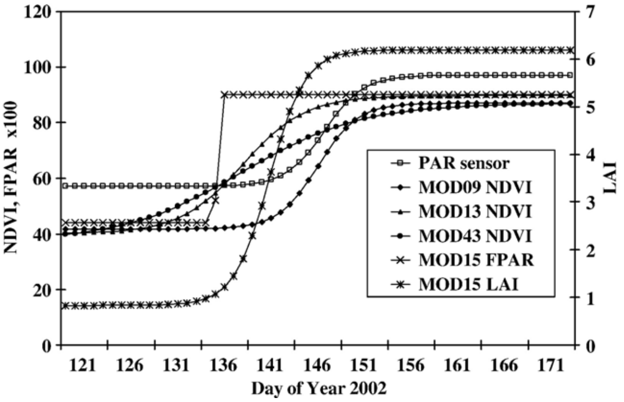

Fig. 3. Modeled spring phenology of a deciduous forest by fitting Eq. (4) to the field data and selected MODIS products.

spring canopy phenology (Table 1). Each product was obtained through the EOS Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). The MOD09 daily surface reflectance products were used to maximize the potential number of days used in estimating phenology. All other MODIS products represented different spatial or temporal compositing. Quality assessment bits from each product indicted data of good quality. In each case we obtained the V004 data which has been "validated over a range of conditions." ERDAS Imagine software was used to reproject data from the sinusoidal to a UTM (zone 16) projection using nearest neighbor resampling. We obtained enough data (dates) to demonstrate and model the greenup period, maximum leaf-on, and stable leaf-off stages. The normalized difference vegetation index (NDVI) was calculated separately from MOD09GQK and MOD43B4 as:

$$\mathrm{NDVI} = \frac{\mathrm{Band2}-\mathrm{Band1}}{\mathrm{Band2}+\mathrm{Band1}} \tag{2}$$

where Band2 represents the near infrared reflectance (871–876 nm) and Band1 represents the red reflectance (620–670 nm) of each product. The Enhanced Vegetation Index (EVI) was calculated from MOD43B4:

$$\mathrm{EVI} = 2.5\frac{\mathrm{Band2}-\mathrm{Band1}}{\mathrm{Band2}+6\mathrm{Band1}-7.5\mathrm{Band3}+1} \tag{3}$$

where Band3 is the blue reflectance (459–479 nm). The coefficients 2.5 and 1 represent the gain and canopy background, respectively (Huete et al., 2002). The atmospheric influence on Band1 is "corrected" using Band3 and the coefficients 6 and 7.5, respectively. We used the NDVI and EVI vegetation indices because these are standard products developed and used from MODIS and have been used previously to characterize phenology. We did not calculate EVI for MOD09GQK because the blue reflectance is not a standard product of MOD09GQK (the EVI calculated in MOD13 250 m uses a disaggregated 500 m blue reflectance).

LAI and FPAR absorbed by the vegetation from MOD15 were chosen for analysis because they are important variables in estimating energy and mass exchange, are directly related to photosynthetic biomass, and have been used previously to estimate phenology (Kang et al., 2003). We note the distinction between FIPAR calculated from field data in Eq. (1) and FPAR from the MOD15 product. The MODIS FPAR algorithm estimates canopy spectral absorptance as: $a(\lambda)=1-(1-\rho(\lambda))t(\lambda)-r(\lambda)$ using canopy spectral invariant relationships and then averaged over the PAR interval, where ρ is the ground reflectance, and t and r are the canopy transmittance and reflectance, respectively (Yang et al., in press-a,b). Eq. (1) ignores ρ and r and includes radiation intercepted by tree stems and branches. However, the difference between FIPAR and FPAR is usually <5% in mature closed stand canopies (Gower et al., 1999).

The layout of the field grid of each site intersected a 3 × 3 matrix of the 250 m pixels of the MODIS products. Given the potential geolocation errors and difficulty in directly matching pixels with field data, we evaluated three methods for extracting pixel values using GPS-derived coordinates of the field sites and corresponding field data: 1) apply a 3 × 3 median filter to the image data and use the closest center pixel value for each site, 2) apply a 3 × 3

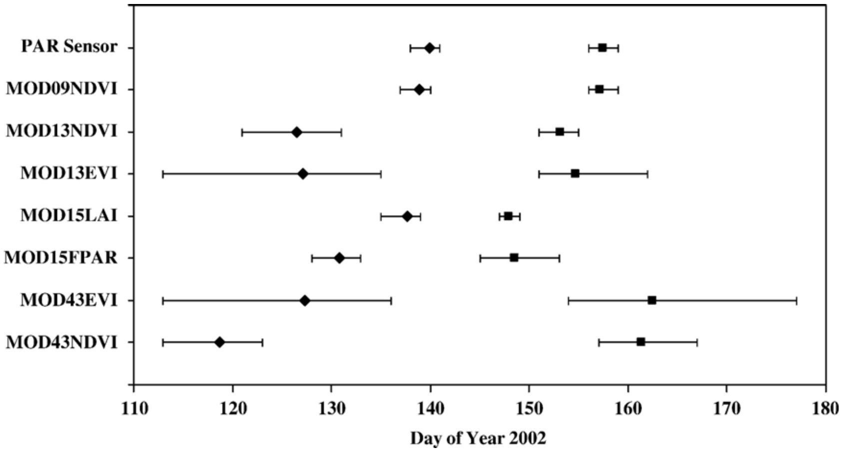

Fig. 4. Average onset of greenness (diamonds) and maturity (squares) with 95% confidence intervals calculated from the Monte Carlo simulation of Eq. (4) for each product.

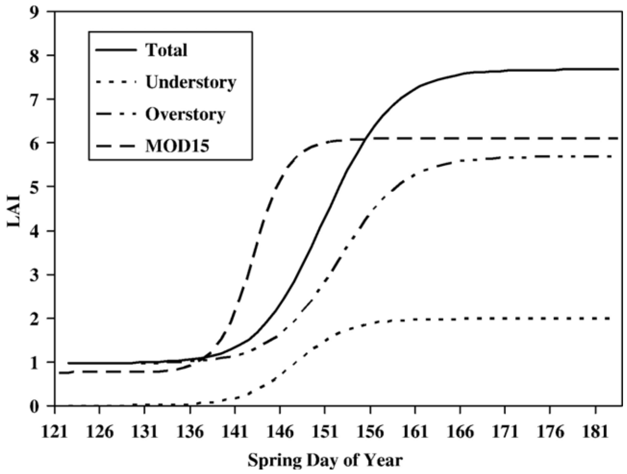

Fig. 5. Spring phenology of leaf area index (LAI) modeled from MOD15 and field data. Understory LAI was estimated using biomass data from Burrows (2002). Total LAI is the sum of the Understory and Overstory.

mean filter and use the closest center pixel value for each site, and 3) use the closest center pixel value of the original product. We examined these methods using NDVI calculated from MOD09GQK and found all methods resulted in mean values within 2.5% or 0.016 NDVI of each other. Therefore, for simplicity we applied the third method (3) to all products assuming errors in geolocation and/or resampling would be minimal.

2.4. Detection of phenological transitions

Zhang et al. (2003) suggest four transition dates which define key phenological phases that may be detected with remote sensing: i) onset of photosynthetic activity or greenness; ii) onset of maturity or LAI maximum; iii) onset of senescence and iv) onset of dormancy. In this study we evaluated remote sensing products for detecting greenness (i) and maturity (ii). A logistic model was fit to each time series of data in SigmaPlot (version 7.1, SPSS Inc., Chicago, Illinois) with the following equation (Zhang et al., 2003):

$$y(t) = \frac{c}{1+e^{a+bt}} + d \tag{4}$$

where $y(t)$ is the vegetation index, FPAR, or LAI value at time t, a and b are empirical coefficients, d is the initial background value, and c is the potential maximum value (vegetation index, LAI, FPAR).

Similar to Zhang et al. (2003, 2004), we calculated the phenological transition dates using the derivative of the curvature in Eq. (4):

$$K' = b^3 cz \left\{ \begin{array}{l} \dfrac{3z(1-z)(1+z)^3\left[2(1+z)^3 + b^2c^2z\right]}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{5}{2}}} \\ -\dfrac{(1+z)^2(1+2z-5z^2)}{\left[(1+z)^4 + (bcz)^2\right]^{\frac{3}{2}}} \end{array} \right\} \tag{5}$$

where $z = e^{a+bt}$. The rate-of-change of curvature of the time series exhibits local minima and maxima which may be related to transition dates (Zhang et al., 2004). For the purpose of this study, we identified the local maximum surrounding the inflection to be associated with the onset of greenness and onset of maturity.

We used Monte Carlo simulations with the MODEL procedure in SAS (SAS, 2000) to examine the sensitivity of the four coefficients in Eq. (4) to estimate the onset of greenness and maturity. For each dataset and fit model, twenty thousand random permutations were generated from Eq. (4) parameters, based on the standard error of each parameter estimate. Transition dates were calculated from each simulation using Eq. (5) as described above. Average transition dates and 95% confidence intervals were then calculated for each simulation dataset.

3. Results and discussion

3.1. Field data

PAI and FIPAR did not differ significantly among the three sites for each of the 4 dates. Averaged over the three sites, PAI ranged from 1.69 on May 27th to 5.73 on June 28th (Table 2). From the field data and personal observations, the period encompassing onset of greenness and onset of leaf maturity occurred during a 10–12 day period. On May 27th, budburst was already occurring for many of the trees (i.e., we captured the beginning of canopy greenup). Much of the ground cover on May 27th was already green. While the single PAR sensor located in Site A provided only one location point of data, it seems a reasonable surrogate for the canopy phenology of all sites, A–C, as the LAI-2000 FIPAR from all sites closely matched that from the PAR sensor (Fig. 2).

3.2. Phenology from MODIS products

Most estimates for onset of greenness and maturity from MODIS products were less than that estimated from the PAR sensor and LAI-2000 (Table 3, Fig. 3). Phenology transition dates using NDVI calculated from MOD09 matched the field data the closest (within 1 day). Results from the Monte Carlo simulations reveal a great deal of uncertainty in estimating transition dates with some MODIS products using a combination of Eqs. (4) and (5) (Fig. 4). The range of plausible dates using these procedures spanned 3 and 23 days for the MOD09 and MOD43 products, respectively. For additional insight, we calculated a plausible error for the MOD09 NDVI (±0.04) based on Vermote et al. (1997) and incorporated that error in the Monte Carlo procedure. Mean transition dates for the MOD09 NDVI with the error term were 138 (±2 days) and 159 (±2 days) for onset of greenness and maturity, respectively, indicating that the error in the MOD09 product for these sites was negligible compared to the field data. Since the MOD13 NDVI is derived directly from MOD09, the only logical explanation for the difference is the 16-day compositing of MOD13 which uses a maximum value approach. The quality assessment bits (MODLAND Mandatory QA) for all MOD13 observations used indicated the indices were produced “with good quality.” The compositing method used for the other products (MOD15, MOD43) also likely contributed to the observed differences in transition dates. This is important because the rapid greenup observed in this study occurred in 10–12 days, which means that a 16- or 8-day composited products could underestimate or overestimate the actual spring canopy phenology signal for this area. However, we note that the data collected in this study is limited to 2002 and that interannual variations should be examined further. MOD13, MOD15, and MOD43 may only provide 1–2 observations during this period. For canopy studies aimed at detecting the effects of climate change, it may be more meaningful if the MODIS product contained information on the date(s) from which the product was developed or weighted most heavily. Development of a combined Terra/Aqua product, possibly increasing the number of available scenes, should also be useful in this context (Yang et al., in press-a,b).

The best agreement between field data and MOD15 LAI occurred after the apparent onset of maturity (Fig. 2a), while the greatest differences occurred during greenup. Based on the data we collected, it is unclear why this is the case in light of the much better matched FPAR data (Fig. 2b), but we offer two possible explanations. First, half of the MOD15 LAI/FPAR values were derived using the backup empirical algorithm rather than main radiative transfer (RT) algorithm. The QA bits indicate these data to be “OK, but not the best” with clouds or aerosols likely contaminating the pixels. The second issue concerns the ability to accurately and quickly measure LAI in the field. Potential problems associated with using the LAI-2000 during greenup include: (i) incorporating total plant area (branches and stem), (ii) ignoring ground and canopy reflectance, and (iii) the error associated with the instrument. The LAI-2000 and the MOD15 LAI algorithm have different sensitivities to LAI variation. The LAI-2000 rejects radiation above 490 nm and provides an estimate of radiation transmitted through gaps. Gap fraction is likely insensitive to LAI at the early stages of canopy development, which could lead to overestimating (later date) onset. Additionally, the field PAI data from this study and others in the same region (see Burrows et al., 2002; Fassnacht & Gower, 1997) suggest that the LAI error associated with the instrument can be approximately 0.5 $m^2\ m^{-2}$. This error could make validation efforts difficult when trying to measure small changes in LAI or vegetation with low LAI.

Complicating factors to consider in this study include spatial scale and within stand heterogeneity. We used the 1 km data from MOD15 and MOD43, whereas our measurements at each site encompassed only 540 m. The landcover and canopy structure (mean LAI) may change slightly outside each immediate site and may contribute to the dilution of the results. However, based on field observations and high resolution imagery, we speculate that off-site effects had minimal influence for this area because the surrounding area is primarily forested with similar deciduous vegetation. The highest standard deviation of within stand PAI was approximately 0.9 despite each stand being of similar age, species, and mean PAI. The spatial heterogeneity of LAI will also contribute to the uncertainty associated with MODIS derived products (Shabanov et al., 2003) and should be considered in future studies of phenology.

We observed an understory component that greened earlier than the canopy, which may explain, in part why, the MODIS products estimated an earlier onset of greenness than the field measurements. Recent satellite-based phenology studies do not directly account for this, yet understory vegetation is an important part of the ecosystem. At a study site near to this one, Burrows et al. (2003) found that understory vegetation comprised 14% of the total aboveground NPP. We estimated the understory development and LAI using biomass data from Burrows (2002) and understory specific leaf area data from Kaelke et al. (2001). The addition of understory phenology to canopy (overstory) has the effect of shifting the greenup period and start of onset closer to that predicted by the MOD15 LAI, but also increases maximum LAI (Fig. 5). However, Tremblay and Larocque (2001) showed that understory phenology can change throughout the season likely due to the changing light environment, despite overstory maximum LAI remaining stable until senescence. Future studies should attempt to separate understory and overstory phenology, possibly using radar or lidar technology.

3.3. Implications for estimating carbon and water exchange

The broader research questions governing the development of vegetation phenology measurement techniques in recent literature concerns the reliable prediction of carbon and water exchange, especially in the context of climate change. It follows that the results of these studies need to be tested against the ecophysiological processes in question. On estimating vegetation phenology transition dates, it is unclear from this study, which MODIS product is ‘best’ or whether the differences presented in this study significantly affect estimating NPP. The literature on phenology makes a distinction between bud-, leaf-, growth-, and reproductive phenology (Sigurdsson, 2001), each of which may be affected differently by environmental conditions (e.g., climate, nutrient availability, or atmospheric CO_2 concentrations). Morecroft et al. (2003) showed that full photosynthetic capacity of *Quercus robur* leaves was reached 50 days after budbreak. Similarly, Reich et al. (1991), studying three deciduous species in Wisconsin, demonstrated that the photosynthetic capacity is not completely developed during greenup. Several scientists have suggested that environmental conditions that favor early greenup increase the annual net ecosystem exchange of CO_2 of forests (Gifford, 1994; Rustad et al., 2001; Tjoelker et al., 1999; Woodwell, 1990). More work is needed to define and test phenology transition periods as estimated by satellite sensors for use in ecosystem modeling. Measuring vegetation phenology from improved satellite-based products (e.g., Shabanov et al., 2005; Yang et al., in press-a,b) could help improve the accuracy of carbon and water budgets derived from ecosystem models.

4. Conclusions

Results indicate that MODIS data products used in this study are sensitive enough to track the general vegetation phenology trajectory during leaf expansion of a deciduous forest in northern Wisconsin in 2002. Important findings and suggestions include:

- For phenological studies in this region, satellite data should have a temporal resolution sufficient enough to capture leaf expansion (<1 week). Although Terra/Aqua have near daily repeat coverage for the area encompassing the sites used in this study, approximately 4 out of 5 days were not useful for analysis due to cloud cover.

- Future analysis should include: near daily measurements with the LAI-2000 or similar field instrumentation in spring and autumn (senescence) for a more complete record. An expanded site analysis should include heterogeneous cover, effects of scaling site level measurements (field or high resolution remote sensing) to the region, and the contribution of ground reflectance.
- Future work should examine the tradeoffs and sensitivity associated with choosing transition dates in the context of ecosystem modeling. The effect of choosing start dates, or using a particular product to do so, on accurate carbon and water modeling is unknown.

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