Determination of spring onset and growing season duration using satellite measurements

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Abstract:

An integrated approach to retrieve microwave emissivity difference vegetation index (EDVI) over land regions has been developed from combined multi-platform/multi-sensor satellite measurements, including SSM/I measurements. A possible relationship of the remotely sensed EDVI and the leaf physiology of canopy is exploited at the Harvard Forest site for two growing seasons. This study finds that the EDVI is sensitive to leaf development through vegetation water content of the crown layer of the forest canopy, and has demonstrated that the spring onset and growing season duration can be determined accurately from the time series of satellite estimated EDVI within uncertainties about 3 and 7 days for spring onsets and growing season duration, respectively, compared to in-situ observations. The leaf growing stage may also be quantitatively monitored by a normalized EDVI. Since EDVI retrievals from satellite are generally possible during both daytime and nighttime under non-rain conditions, the EDVI technique studied here may provide higher temporal resolution observations for monitoring the onset of spring and the duration of growing season compared to currently operational satellite methods.

1. Introduction

Earlier springs and wetter autumns over the last two decades due to climate variations and changes resulted in a lengthening of the vegetation carbon uptake period that could account for two thirds of the increase in observed forest growth rates [Goulden et al, 1996; Nemani et al, 2003]. Accurate assessments of spring onset and growing season duration are crucial to estimate CO_2 absorptions by ecosystem in global carbon cycle [Cayan et al, 2001;

Nemani et al, 2002]. Currently, most of the existing techniques in determining vegetation growing season duration and greenness level from satellite remote sensing are based on the normalized difference vegetation index (NDVI) at visible and near-infrared (VIS/NIR) wavelengths [Asrar et al. 1984, Sellers 1985, Myneni et al. 1995]. Vegetation index derived from the optical technique is strongly influenced by clouds and aerosols and only available during daytime, which limits its temporal resolution and the accuracy of the detection of spring onset and determination of growing season duration [Gutman and Ignatov, 1995; Gutman, 1999]. Furthermore, NDVI is saturated when the leaf area index (LAI) is greater than 3, thus losing its sensitivity to detect dense vegetation (e.g. forest) [Hatfield et al, 1985]. Vegetation also significantly modulates the microwave emission from the surface. The microwave land surface emissivity (MLSE) derived from satellite measurements is strong related to vegetation water content (VWC) and canopy structure [Jackson and Schmugge, 1991; Wigneron et al., 1993; Njoku, 1999; Wigneron et al., 2003; Min and Lin, 2005], and less influenced by atmospheric properties, such as clouds and aerosols, than the land surface reflections measured from VIS/NIR wavelengths. Moreover, MLSE can be retrieved during day and night, substantially increasing temporal sampling rates for ecosystem applications.

In a recent study, Min and Lin [2005] have exploited using a combined retrieval of microwave, infrared, and visible measurements to estimate the land surface microwave emissivity difference index (EDVI). They found that the EDVI values could be used to represent physical properties of crown vegetation such as vegetation water content of crown canopies. The collocated land surface turbulent and radiative fluxes were empirically linked together by the EDVI values. Combining retrieved EDVI with radiation measurements, they inferred land surface-atmosphere exchange of moisture and CO_2 at dense forest environments. In this paper, we further exploit potentials of EDVI, along with VIS/NIR and broadband solar radiation measurements, for detecting the spring onset and determining the growing season duration.

2. Methodology and measurements

2.1 Microwave emissivity difference vegetation index (EDVI)

There is a semi-empirically linear relation between the optical depth at microwave wavelengths and vegetation water content (VWC), which varies systematically with both wavelength and canopy structure [Jackson and Schmugge, 1991]. The microwave surface emission above a canopy is an integration of the microwave radiation from the whole canopy vertical profile weighted by its transmission. The microwave land surface emissivity difference between two wavelengths minimizes the influence of the soil emission underneath vegetation canopy and indicates VWC and other vegetation properties of the canopy. Some studies even found that the brightness temperature difference at two microwave wavelengths has certain capability to classify land surface type and to determine forest characteristics [Neale et al. 1990; Pulliainen et al. 1999; Macelloni et al. 2003]. Thus, a new parameter based on the microwave land surface emissivity difference between two wavelengths have been proposed to indicate VWC and other vegetation properties of the canopy with a minimal influence of the soil emission underneath vegetation canopy [Min and Lin, 2005]. Analogous to NDVI and the frequency index of Macelloni et al., the new parameter, microwave emissivity difference vegetation index (EDVI), is defined as:

$$\mathrm{EDVI_P} = \frac{\mathrm{MLSE_P^{19}} - \mathrm{MLSE_P^{37}}}{0.5(\mathrm{MLSE_P^{19}} + \mathrm{MLSE_P^{37}})}$$

where p represents a polarization at vertical or horizontal direction; 19 and 37 indicate 19.4 GHz and 37.0 GHz channels of Special Sensor Microwave/Imager (SSM/I) measurements, respectively. Generally, microwave emissivity retrievals at the longer wavelength with a weaker attenuation by the vegetation water in the canopy represents an effectively thicker layer than those observed at the shorter and stronger attenuation wavelength. Thus, EDVI represents the canopy properties of VWC and structure of two effective emission layers. Min and Lin [2005] also used a simple conceptual two-layer model for microwave radiative transfer calculations to illustrate the fundamental physical linkage of EDVI to crown canopy VWC in heavy forest environments. The study demonstrated that EDVI is insensitive to the soil moisture and has a near-linear relation to the VWC for the range of VWC in some canopies.

We have retrieved MLSE values from the SSM/I data from Defense Meteorological Satellite Program (DMSP) F13 and F14 satellites from1999 to 2001 at the Harvard Forest site (42.54N, 78.18W) for all SSM/I wavelengths and polarizations using a combined technique from multi-sensor/multi-platform measurements [Min and Lin, 2005; Lin and Minnis 2000]. Since the coverage of forest at Harvard Forest within the footprint of 19 GHz channels (69x43 km^2, the largest of SSM/I) is very high, the possible heterogeneity contribution of forest to the emissivity is minimal. As indicated by the study of Min and Lin [2005], the vertical component of the EDVI has a higher correlation with the evapotranspiration than the horizontal component. We will use the $EDVI_V$ in this study.

2.2. Determination of spring onset and growing season duration

To quantitatively determine the spring onset from satellite microwave measurements, the timing of an abrupt increase in the $EDVI_V$, we apply a Lowess smooth algorithm (10 days) on retrieved $EDVI_V$ values to minimize small daily fluctuations caused by uncertainties in retrievals and growing stage variations of various vegetation types. We, then, locate the maximum variation of $EDVI_V$ change rates (curvature point) from the locally smoothed time series of $EDVI_V$ in three steps: 1) take the first derivative in a range (28) of days when the spring onset may occur (+/- 14 days); 2) find the maximum of the second derivative; 3) in case of missing data around the day of the maximum, determine the day of the maximum using a quadratic function. Figure 1 illustrates the procedure based on the data of year 1999. Figure 1a shows the smoothed time series of $EDVI_V$ between day 110 and day 138, a period in which the possible onset of spring may occur. Figure 1b and 1c show the first and second derivatives of $EDVI_V$ as a function of time. Since data on day 129 was missing, we interpolate the second derivative value on day 129 based on a quadratic fit from the second derivatives on days 127, 128, and 130 (solid curve of Fig. 1c). For this case, the quadratic interpolation value on day 129 was less than the second derivative at day 128. Therefore, day 128 is the time of the maximum curvature, i.e. the spring onset of year 1999. The same steps are applied to the tail-end period of a growing season to detect the maximum of the second derivative, i.e., the end of the growing season. Once the spring onset and the end of the growing season have been detected, the growing season duration is decided by the period between the two.

2.3. The normalized EDVI

To quantify the cycle of leaf development, we further define a normalized $EDVI_V$ as:

$$ {}^{N}EDVI_V = \frac{EDVI_V - EDVI_V^{onset}}{EDVI_V^{max} - EDVI_V^{onset}} $$

where $EDVI_V^{onset}$ and $EDVI_V^{max}$ are $EDVI_V$ at the spring onset and the maximum $EDVI_V$ during the growing season, respectively. The ${}^{N}EDVI_V$ is the relative change of $EDVI_V$ from its spring onset value during a growing season and represents the leaf growing stage during the growing season.

3. Results

Annual cycles of vegetation development provide an ideal experiment to determine physical processes of vegetation controlling surface exchanges of carbon and water, particularly to monitor the cycle of leaf emergence and fall in a deciduous forest. We use in situ observations from the Harvard Forest site, where the forest is 50-70 years old and contains a mixture of red oak, red maple, and hemlock with an average tree height of 24 m, to validate satellite estimates. At the Harvard Forest site, the timing of woody vegetation development during the growing season has been observed at 3-7 day intervals [O'Keefe, 2004]. The nature of the forest for spring onset and end of growing season may not be a single day but a short period due to multiple species. In this study, the averaged time of observed initial bud break over four representative species at Harvard Forest (red oak, white oak, red maple, and yellow birch) is defined as the spring onset in the area. The same procedure of averaging applies to observed 75% leaf development and 50% leaf fall to represent the time of those events at the site.

At the Harvard Forest site, up-welling and down-welling radiation sensors mounted on an observation tower measure the surface shortwave (SW) and photosynthetically active radiation (PAR) albedos. The reflectivities at SW and PAR wave bands provide additional information on vegetation conditions and canopy growing stages [Moore et al. 1996; Sakai et al. 1997]. Figure 2 shows retrieved ${}^{N}EDVI_V$ from combined overpasses of F13 and F14 for the growing season of year 2000. We will mainly discuss the results from 2000 and will briefly provide the results from 1999 due to more missing data in the year 1999. We also include measured SW albedo, PAR albedo, and carbon uptake flux from tower measurements, plus NDVI values derived from Advanced Very High Resolution Radiometer (AVHRR; http://daac.gsfc.nasa.gov/data/dataset/avhrr/). These NDVI estimates are the

10-day composite values. The coarse temporal resolution of the data is caused by various environmental conditions, such as clouds, aerosols and availabilities of solar spectrum measurements (i.e., daytimes). The vertical lines indicate the averaged day of year (DOY) from in-situ observations of bud break, 75% leaf development, and 50% leaf fall, respectively. The horizontal bars in each of the three corresponding leaf development stages represent the time ranges (or uncertainties) for all four major species of trees around the Harvard Forest site. These time ranges generally vary from 3 to 15 days (c.f. Table 1) reflecting the nature of the differences in tree species. After the spring onset on DOY 128, ${}^{N}EDVI_{V}$ increased quasi-linearly in the first 20 days accompanied by leaf emergence until 75% leaf had developed. The ${}^{N}EDVI_{V}$ reached to value 0.75 on DOY 153, four days ahead of the averaged day of 75% leaf development of in situ observations at the surface site. It took an additional month for ${}^{N}EDVI_{V}$ to reach its maximum. Leaf senescence is a slow process, occurring in the fall. There was no in situ observations on the onset of senescence. The decrease trend of ${}^{N}EDVI_{V}$ from DOY 260 to the end of growing season indicates reduction of VWC and/or leaf areal coverage, representing the period of leaf senescence process. The timing of ${}^{N}EDVI_{V}$ decreasing to 0.5 on DOY 285 was close to the averaged day of 50% leaf fall observed at the surface on DOY 289, well within the uncertainty of surface observations. As ripen process proceeds, ${}^{N}EDVI_{V}$ further decreased substantially into small even negative values. At the end of the growing season on DOY 302, ${}^{N}EDVI_{V}$ was about zero. After that day, ${}^{N}EDVI_{V}$ went to negative, indicating that the canopy as a whole may be drier than the beginning of the growing season. After DOY 321, ${}^{N}EDVI_{V}$ ended its decrease and stayed at a constant value, indicating the end of leaf fall.

Surface albedos at optical wavelengths directly link to the characteristics of surface properties, as a result of absorption and reflection of canopy. The surface SW albedo derived from tower measurements increased rapidly in the early spring, consistent with the variations of ${}^{N}EDVI_{V}$. However, the SW albedo reached its maximum before 75% leaf development and then gradually decreased throughout the rest of the growing season. The SW albedo started an abrupt drop 10 days after 50% leaf fall. NDVI retrievals from AVHRR show much coarser temporal resolution due to the limit of clear-sky conditions than that of ${}^{N}EDVI_{V}$. Small NDVI values, occasionally shown in the middle of the growing season, may result from some cloud contaminations. Generally, the temporal variation of NDVI closely follows that of SW albedo, since they are all based on reflections in solar spectra.

In the meantime, the PAR albedo, shown in the bottom panel of Figure 2, illustrated a gradual decrease at the beginning of the growing season due to increases in the absorption of solar radiation at the PAR spectra caused by enhancing photosynthetic processes of the canopy. The gradual decrease of PAR albedo ended around DOY 170, approximate 10 days before ${}^{N}EDVI_{V}$ reached its maximum, and then PAR albedo stayed nearly constant for the rest of the growing season until the leaf senescence. The increase of PAR albedo, then, occurred on DOY 275 before 50% leaf fall indicating reduction of photosynthesis as a consequence of changing leaf color. Comparing to the variations of ${}^{N}EDVI_{V}$ in both early growing season (DOY 170-180) and leaf senescence (DOY 265-275), PAR albedo was apparently saturated to the development of leaf stage as LAI of canopy was high. The reason is that the penetration and reflection of photons at the optical wavelengths are limited to the top layer of the crown layer of a forest canopy, resulting surface albedos insensitive to leaf development of subcanopy. Microwave emission, on the other hand, is relatively easier penetrating through a deeper crown layer of a forest than that at PAR wavelengths, thus a better way to detect the growing stage of entire canopy. This result indicates the ${}^{N}EDVI_{V}$ may provide a better tool to estimate growing season duration than those from solar wavelengths.

Because of the strong relationship between EDVI and physical properties of crown layer of canopy as discussed in previous sections, the temporal variation of EDVI should be consistent with that of observed carbon uptake flux. Min and Lin [2005] did find that there is statistically significant relationship with the correlation coefficient of 0.74 between CO_2 uptake fluxes and the products of the EDVI and surface PAR measurements at Harvard Forest for all-weather conditions (both cloud and clear-sky). As pointed out by Min [2005], radiation-use-efficiency varies significantly from clear-sky, to partially cloudy, and to overcast conditions. The correlation (with the coefficient 0.97) of EDVI with CO_2 fluxes for clear-sky cases is stronger than not only that of all-sky cases but also those using NDVI [Min and Lin, 2005]. The timing of decrease in ${}^{N}EDVI_{V}$ in the late summer reflects the first sign of leaf senescence. When $EDVI_{V}^{N}$ decreased significantly even below zero in the end of growing seasons, the carbon uptake fluxes were also near zero, indicating no noticeable photosynthetic activity in the periods. However, SW reflections during these periods were significant higher than that during off-growing season, which is inconsistent with forest physiology. The physiological processes associated with leaves have an annual cycle shorter than that of their physical presence. The variations of ${}^{N}EDVI_{V}$ during summer time were also resulted from the physiologically dynamic characteristic of forest. Other factors such as water stress may have significant impact on forest. It is worthwhile to notice that sky conditions (aerosols and clouds) have limited impacts on surface derived albedos from tower measurements, and the temporal resolution of surface albedo used in this study is much better than that of most vegetation indexes derived from satellite optical observations because of strongly atmospheric influence on satellite retrievals. Thus, even with these merits of the surface measurements, the ${}^{N}EDVI_{V}$ still shows advantages in monitoring forests.

The characteristics of detecting leaf development in year 1999 are similar to that of year 2000, shown in Figure 3, although some surface measurements were missed in that year. Table 1 summarizes the days of leaf growth stages, observed at surface for four major species and inferred from ${}^{N}EDVI_{V}$. We also include the leaf growth stages estimated from the time series of measured SW albedo using the same procedure for comparison. For each overpass of each DMSP satellite, ${}^{N}EDVI_{V}$ demonstrates its capability to monitor various stages of leaf development within the uncertainty of ground observation. ${}^{N}EDVI_{V}$ derived stage times of leaf development from the average of all overpasses (morning and afternoon, F13 and F14) provide the most accurate assessment of the spring onset and the growing season duration.

Table 1. Observed and inferred growing stages of leaf at the Harvard Forest site in years of 1999 and 2000.

	1999				2000			
	The Spring onset	75% leaf development	50% leaf fall	The end of season	The Spring onset	75% leaf development	50% leaf fall	The end of season
Red Oak	126	148	294	-	129	161	293	-
Red Maple	126	146	286	-	129	156	283	-
Yellow Birch	127	141	287	-	129	149	283	-
White Oak	132	155	301	-	132	162	298	-
Mean	128	148	292	-	130	157	289	-
F13_AM	129	160	255	308	-	-	-	-
F13_PM	129	148	276	312	-	-	-	-
F14_AM	-	-	-	308	129	160	287	298
F14_PM	-	-	-	299	130	172	283	324
F13&F14	127	154	280	306	130	153	285	321
SW_albedo	132	-	-	312	127	-	-	316

4. Summary and discussion

Making a connection between remotely sensed data and canopy physiology is extremely useful for studies of regional and continental scale land surface properties. Through its influence on the radiation fields of forest canopies and the restriction of momentum exchange of atmosphere and surface, the seasonally changing leaf physiology of canopy has a dramatic impact not only on the land and atmosphere exchange of moisture evapotranspiration and CO_2 uptake fluxes, but also on subcanopy exchange processes. In this study, we exploited a possible linkage of remotely sensed entities, surface albedo at optical wavelengths and land surface microwave emissivity difference index, to the leaf physiology of canopy at the Harvard Forest site. The maximum curvature technique developed in this study is used to detect the spring onset and growing season duration from time series of $EDVI_V$. Furthermore, we used the normalized EDVI to quantify canopy leaf development. Surface albedos at SW and PAR wavelengths are only sensitive to the leaf development of the uppermost part of the crown layer of forest canopies, and lack information for subcanopy layers of forests when canopy LAI is high. Thus, surface albedos (and associated indexes) at optical wavelengths alone cannot accurately represent the growing stage of a canopy. However, microwave radiation has much better penetration for vegetated areas than that at optical wavelengths, ensuring that ${}^{N}EDVI_{V}$ is more sensitive to large parts of the column of a canopy. Furthermore, retrievals of $EDVI_V$ from satellite microwave measurements are generally possible during day and night under most atmospheric conditions (except for precipitation). The microwave technique provides higher temporal resolution on monitoring the onset of spring and determining the duration of growing season than reflection measurements at the optical wavelengths. As demonstrated, not only the spring onset and growing season duration can be determined accurately from a time series of $EDVI_V$, but also the leaf growing stage can be quantitatively monitored. This study also supports the fundamental conclusion of our previous study [Min and Lin, 2005] that a combined retrieval of microwave, infrared, and visible measurements from satellite can accurately estimate land surface-atmosphere exchange at dense forest environments. The shortcoming of satellite microwave measurements is their lower spatial resolution than that of VIS/NIR observations. Combining visible, near-infrared, infrared, and microwave measurements would substantially reduce the ambiguities inherent in individual spectral regime, and increase effective temporal and spatial sampling rates of required datasets for remotely sensing forest-atmosphere exchange.

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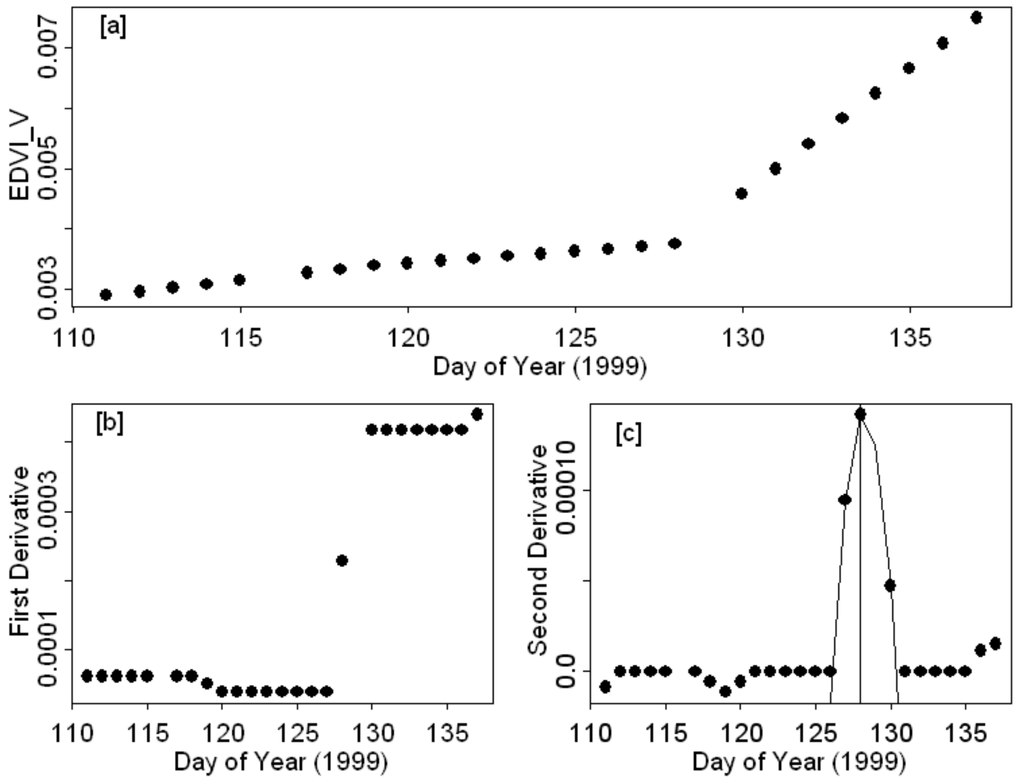

Figure 1. Smoothed EDVI_V between days 110 and 135 of year 1999 (up panel), and its first and second derivatives (bottom panels)**.**

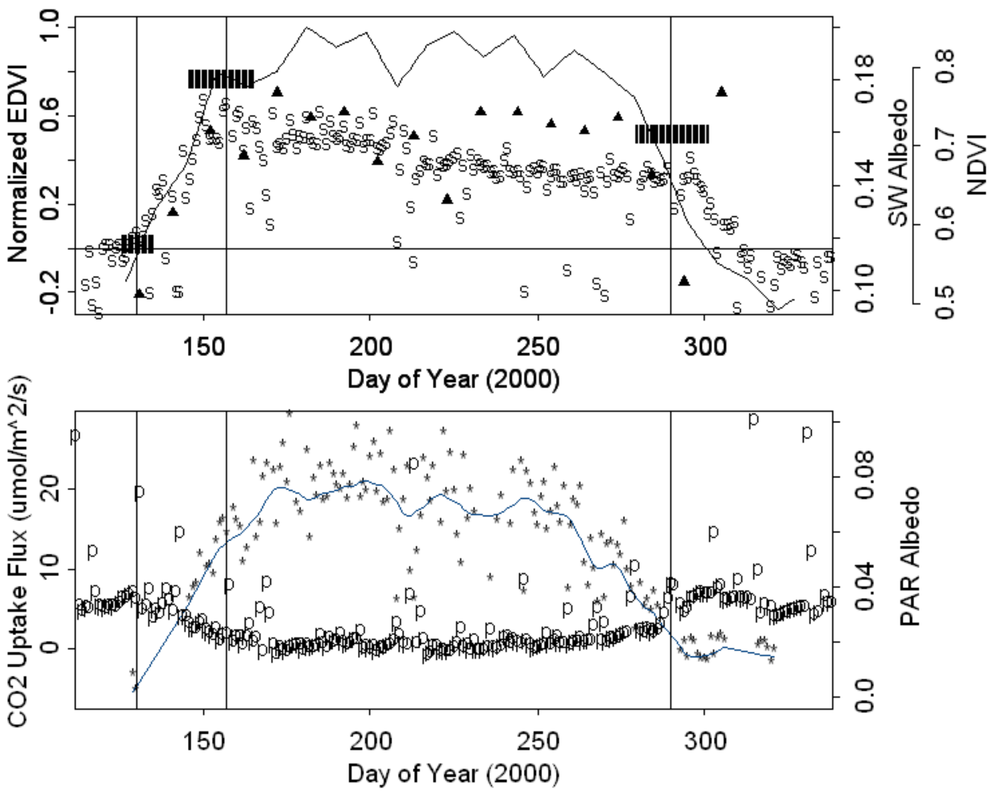

Figure 2. Multi-sensor/multi-platform measurements at the Harvard Forest site for the growing season of 2000. Upper panel: $^{N}EDVI_{V}$ (solid curve), NDVI (soild triangle), and SW albedo ("s"); lower panel: CO_2 uptake flux (dots with the averaged values as smoothed solid curve), and PAR albedo ("p"). The vertical lines indicate the averaged DOY from in-situ observations of bud break, 75% leaf development, and 50% leaf fall, respectively. The horizontal bars represent the time range in each of the three corresponding leaf development stages.

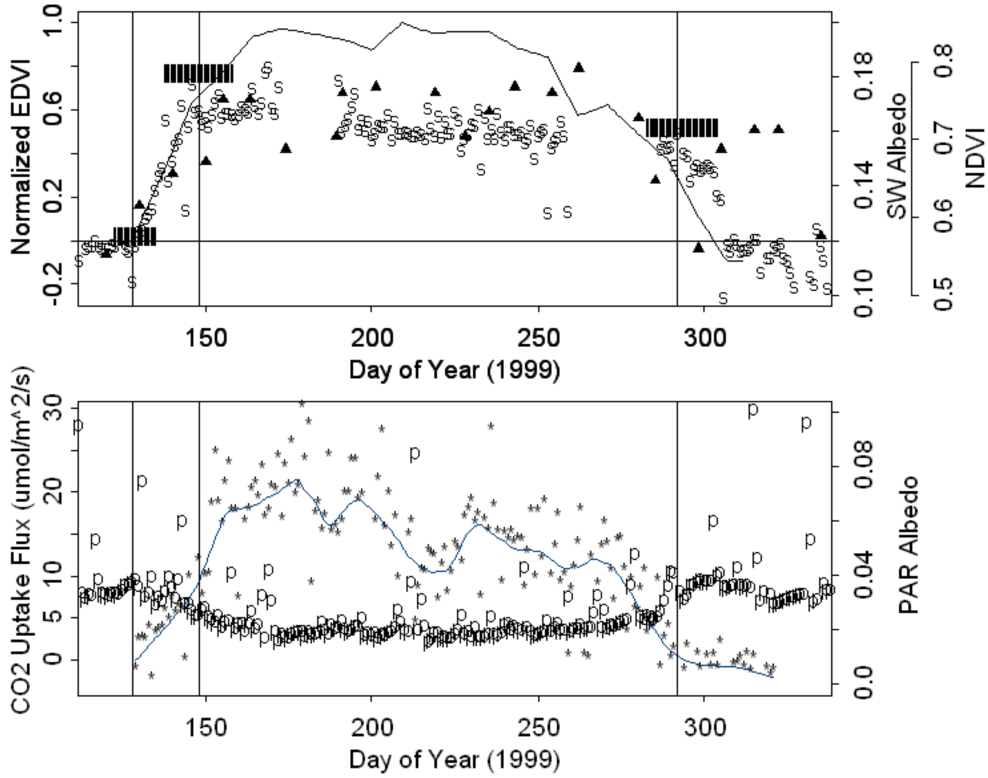

Figure 3. The same as Figure 2 but for the growing season of 1999.