Land Surface Phenology: Convergence of Satellite and CO_2 Eddy Flux Observations

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Abstract Land surface phenology (LSP) is a key indicator of ecosystem dynamics under a changing environment. Over the last few decades, numerous studies have used the time series data of vegetation indices derived from land surface reflectance acquired by satellite-based optical sensors to delineate land surface phenology. Recent progress and data accumulation from CO_2 eddy flux towers offers a new perspective for delineating land surface phenology through either net ecosystem exchange of CO_2 (NEE) or gross primary production (GPP). In this chapter, we discussed the potential convergence of satellite observation approach and CO_2 eddy flux observation approach. We evaluated three vegetation indices (Normalized Difference Vegetation Index, Enhanced Vegetation Index, and Land Surface Water Index) in relation to NEE and GPP data from five CO_2 eddy flux tower sites, representing five vegetation types (deciduous broadleaf forests, evergreen needle-leaf forest, temperate grassland, cropland, and tropical moist evergreen broadleaf forest). This chapter highlights the need for the community to combine satellite observation approach and CO_2 eddy flux observation approach, in order to develop better understanding of land surface phenology.

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1 Introduction

Phenology is the study of periodic biological events in the animals and plants (Lieth 1974; Schwartz 2003). Plant phenology is often studied in a hierarchical structure, ranging from plant organs (first leaf, first flower), individual plants, (% leaf expansion, % flowering), community (% of vegetation) to landscape. Phenology of animals and plants are sensitive to changes in weather and climate. Changes in phenology of plants will affect the carbon cycle, water cycle and energy fluxes through photosynthesis and evapotranspiration, which are closely related to food security, water resources availability and climate.

Numerous in situ observations from researchers and volunteers (e.g. gardeners) have documented various phenological phases of plants (e.g. leaf-on, fall leaf coloring and leaf-off, date of the first flowering) over years. For instance, in situ plant phenology data have been collected at the Hubbard Brook and Harvard Forest Long-Term Ecological Research (LTER) sites for several decades and these data clearly document a marked trend towards an earlier onset of spring over the years (Richardson et al. 2006).

The satellite-based Earth observation systems in 1980s opened a new frontier in the field of phenology from the landscape perspective. Satellite-based optical remote sensing platforms (e.g. NOAA AVHRR sensors) provided daily observations of the land surface for the entire Earth, and the land surface reflectance as recorded in the optical sensors are associated with the biophysical and biochemical properties of vegetation and soils. Vegetation indices, a mathematical transformation as calculated from surface reflectance of different spectral bands (e.g. red and near infrared), have been widely used to track vegetation dynamics in the land surface. The Normalized Difference Vegetation Index (NDVI), calculated from images of NOAA AVHRR sensors, is now the longest time series data for phenology study, and the results from the analysis of AVHRR-based NDVI revealed significant changes in spring phenology of vegetation in 1980s–1990s (Myneni et al. 1997; White et al. 2005). Recently, phenology data products were generated by the Science Team of the Moderate Resolution Imaging Spectroradiometer (MODIS), as part of the NASA Earth Observing System (EOS) program (Zhang et al. 2006, 2003).

The CO_2 eddy covariance method and instrument system in 1990s also opened a new frontier in the field of phenology from the ecosystem and landscape perspective. Continuous CO_2 flux measurements at CO_2 eddy tower sites over a year offer unprecedented opportunity to quantify phenological phases at the ecosystem- and landscape levels from the eco-physiological perspective. It is thought that even modest changes in the length or magnitude of the plant growing season could result in large changes in annual gross primary production in deciduous broadleaf forests (Goulden et al. 1996). An analysis of net ecosystem exchange of CO_2 (NEE) between forest ecosystems and the atmosphere during 1991–2000 in Harvard Forest also suggested that weather and seasonal climate (e.g. light, temperature, and moisture) regulated seasonal and interannual fluctuations of carbon uptake in a temperate deciduous broadleaf forest (Barford et al. 2001). Nowadays, there are more than 600 eddy flux tower sites in various biomes of the world; and these CO_2 flux sites formed several networks (e.g. AmeriFlux, ChinaFlux, EuroFlux and AsiaFlux). The networks of CO_2 eddy flux tower sties play an increasing important role in determining whether individual ecosystems are carbon sink or carbon source (Baldocchi et al. 2001).

Availability of large-volume and valuable datasets from both CO_2 eddy flux towers and satellite remote sensing offer unprecedented opportunity to cross-validating the phenological observations at ecosystem and landscape levels, as observed from the satellite approach and flux tower. It makes possible to address the following scientific questions: To what degree will the photosynthetically active period as delineated by GPP be consistent with the phenology as delineated by satellite observations? Which vegetation index is better to delineate land surface phenology (land surface dynamics in spring and fall)? Can several vegetation indices be used together to improve delineation of land surface phenology? Will phenology delineated from eco-physiological approach and satellite observation approach be consistent with the phenology delineated from the bio-climatic approach and *in situ* observations (scaling-up from in situ individual plants to landscapes)?

In this chapter, we present the data from CO_2 eddy flux towers and satellite images over several terrestrial ecosystems. Our objective is to illustrate the (1) usefulness of CO_2 eddy flux data for delineating phenology of terrestrial ecosystems from the perspective of eco-physiology; and (2) sensitivity of three vegetation indices derived from satellite images for delineating land surface phenology from the perspective of satellite-based Earth observation. These case studies may shed some light on the potential convergence between satellite observation approach and tower-based eco-physiological approach.

2 Methods

In this chapter we focused on land surface phenology (LSP) and vegetation phenology: Vegetation phenology (plant community level or ecosystem level) describes plant phenology for all species in a plant community, or vegetation. In situ observations of individual ecosystem types are often carried out at a specific location, and document differentiated dynamics of individual species of a plant community in responses to climate. Land surface phenology (landscape level) describes temporal dynamics of landscape that is often a mix of soil, vegetation, water bodies, etc. Phenology at the landscape scale poses challenge to observers, because of its complexity; and it often generates confusions among observers because observers may use different approaches. Research approaches for land surface phenology could be roughly grouped into three categories by their observation platforms: meteorological observation; satellite-based reflectance; and CO_2 eddy flux tower.

Meteorological Approach. The first major approach is based on meteorological measurements at weather stations (Lieth 1974; White et al. 1997). For example, frost-free period is a good indicator for plant growing season length; cumulated temperature over 0°C, 5°C is often used to delineate the starting date of the plant growing season. The meteorological approach has the longest history in phenology, and is often incorporated into vegetation models to predict future change of phenology in response to climate change in twenty-first century, or to re-construct phenology in the past.

CO_2 Eddy Flux Tower Approach. The second major approach is the eco-physiological approach, based on eddy flux tower platforms (Churkina et al. 2005). The eddy covariance technique measures net exchange of CO_2 and water between terrestrial ecosystems and the atmosphere, and energy fluxes at very short time interval (10 Hz aggregated to 30 min) over years, which together provide precise measurements of ecosystem metabolisms over time (Wofsy et al. 1993; Baldocchi et al. 2001; Falge et al. 2002). Since the early 1990s, hundreds of eddy flux tower sites have been established and cover all major biome types in the world. The footprint size of an eddy flux tower site varies, dependent upon many factors such as the height of the tower, wind speed, and topography, and it ranges from hundreds of meters to a few kilometers. It is important to note that the footprint sizes of CO_2 eddy flux tower are comparable to the spatial resolution of several major satellite observation platforms (e.g. MODIS, VGT). Therefore, several studies have compared the dynamics of satellite-derived vegetation indices with CO_2 fluxes from the flux towers, in an effort to establish the linkage between ecosystem metabolism (CO_2 flux) and satellite-based observation of vegetation dynamics (Xiao et al. 2004b). In this chapter, our discussion focuses on both satellite-based approach and CO_2 flux tower approach.

Satellite-Based Surface Reflectance Approach: The third major approach is based on space-borne satellite observations. Satellite observations provide information on changes in biophysical (e.g. leaf area index) and biochemical (e.g. chlorophyll content, water content) parameters in the land surface (Zhang et al. 2005). Time series of NDVI data derived from AVHRR data since 1980 highlight its potential for monitoring land surface phenology (Stockli and Vidale 2004; White et al. 2005; Philippon et al. 2007). NDVI-derived land surface phenology was often evaluated with time series data of ground-based plant phenology, and the results from a recent study in Switzerland over 1982–2001 indicated that satellite-derived phenology is very susceptible to snow cover (Studer et al. 2007).

2.1 CO_2 Eddy Flux Tower Approach for Land Surface Phenology

Application of eddy covariance technique to measures net ecosystem exchange (NEE) of CO_2 between terrestrial ecosystems and the atmosphere dates back to 1974 (Shaw et al. 1974). In 1990, the first year-long continuous CO_2 flux measurements by eddy covariance technique were conducted at Harvard Forest site, Massachusetts (Wofsy et al. 1993). CO_2 flux tower sites provide integrated CO_2 flux measurements over footprints with sizes and shapes (linear dimensions typically ranging from hundreds of meters to several kilometers) that vary with the tower height, canopy physical characteristics and wind velocity (Baldocchi et al. 1996).

The NEE of CO_2 between the terrestrial ecosystem and the atmosphere, as measured at half-hourly interval throughout a year, is the difference between gross primary production (GPP) and ecosystem respiration (Reco):

$$NEE = GPP - Reco \tag{1}$$

An analysis of NEE from 1991 to 2000 at Harvard Forest suggested that weather and climate (e.g. light, temperature and moisture) regulated seasonal and interannual fluctuations of carbon uptake in a temperate deciduous broadleaf forest (Barford et al. 2001). A number of other studies have demonstrated a major role for plant growing season length (GSL) in the terrestrial carbon cycle (Myneni et al. 1997; White et al. 1999). An earlier study used NEE data from 28 flux tower sites to delineate a carbon uptake period (CUP), defined as the number of days with negative NEE values (net CO_2 uptake by terrestrial ecosystems), and then used CUP as an approximate estimate of GSL (Churkina et al. 2005). There is a strong correlation between annual NEE and CUP for temperate broadleaf forests (Baldocchi and Wilson 2001; White and Nemani 2003).

Partitioning of NEE into ecosystem respiration and GPP is an active research field (Falge et al. 2002), and the resultant GPP data offers a way to delineate the plant photosynthetically active period (PAP), defined as the number of consecutive days with GPP values of greater than zero (or a threshold value, for example, 1 g C m^{-2} day^{-1}, if given some estimates of uncertainty in NEE measurements and estimation of ecosystem respiration). The PAP can be used as an approximate estimate of GSL.

Both CUP and PAP are definitions from the perspective of eco-physiological approach, and theoretically PAP may have stronger correlation with GSL and vegetation indices than does CUP, because the latter is also affected by ecosystem respiration. In this chapter we examine the relationships between vegetation indices with both NEE and GPP.

2.2 Satellite-Based Approach for Land Surface Phenology

2.2.1 Spectral, Spatial and Temporal Characteristics of Optical Sensors

The time series data of from the following three optical sensors have been widely used for phenological studies.

The Advanced Very High Resolution Radiometer (AVHRR) Sensors. The AVHRR sensor was originally designed for weather and climate study, and aims to provide radiance data for investigation of clouds, snow and ice extent, temperature of radiating surface and sea surface temperature. It has two spectral bands: red band (580–680 nm) and near infrared (725–1,100 nm), and acquires daily images for the globe at 1-km to 4-km spatial resolution. Numerous studies have used these two spectral bands to study vegetation condition (Myneni et al. 1997). However AVHRR data has some limitation for vegetation studies such as lack of calibration, poor geometry and high level of noise due to large pixel size and limited cloud screening (Goward et al. 1991).

The Vegetation (VGT) Sensors: The VGT sensor onboard the SPOT-4 satellite was launched in March 24, 1998, as the first space-borne moderate resolution sensor designed for vegetation study. The VGT sensor onboard the SPOT-4 satellite has four spectral bands: blue (430–470 nm), red (610–680 nm), near infrared (NIR, 780–890 nm) and shortwave infrared (SWIR, 1,580–1,750 nm). The sensor has a spatial resolution of 1,165 m × 1,165 m and a swath of 2,250 km. VGT sensor onboard the SPOT-5 satellite was launched on April 5, 2002, and is still operational. The VEGETATION program is co-financed by the European Union and conducted under the supervision of CNES (National Centre for Space Studies, France). The VGT program provides daily and 10-day synthesis (composite) products at 1-km spatial resolution. The standard 10-day composite data (VGT-S10) are freely available to the public (http://free.vgt.vito.be). The temporal compositing method for generating standard 10-day synthetic products (VGT-S10) is to select an observation with the maximum NDVI value within a ten-day period. There are three 10-day composites within a month: day 1–10, day 11–20, and day 21 to the end of the month.

The MODerate resolution Imaging Spectroradiometer (MODIS) Sensors: The MODIS sensor onboard the NASA Terra satellite was launched in December 1999. The MODIS sensor has 36 spectral bands, seven of which are designed for the study of vegetation and land surfaces: blue (459–479 nm), green (545–565 nm), red (620–670 nm), near infrared (NIR1: 841–875 nm; NIR2: 1,230–1,250 nm), and shortwave infrared (SWIR1: 1,628–1,652 nm, SWIR2: 2,105–2,155 nm). Daily global imagery is provided at spatial resolutions of 250-m (red and NIR1) and 500-m (blue, green, NIR2, SWIR1, SWIR2). The MODIS Land Science Team provides a suite of standard MODIS data products to the users, including the 8-day composite MODIS Surface Reflectance Product (MOD09A1). Each 8-day composite (MOD09A1) includes estimates of surface spectral reflectance for the seven spectral bands at 500-m spatial resolution. In the production of MOD09A1, atmospheric corrections for gases, thin cirrus clouds and aerosols are implemented (Vermote and Vermeulen 1999). MOD09A1 composites are generated in a multi-step process that first eliminates pixels with a low observational coverage, and then selects an observation with the minimum blue-band value during an 8-day period (http://modis-land.gsfc.nasa.gov/MOD09/MOD09ProductInfo/MOD09_L3_8-day.htm).

2.2.2 Vegetation Indices

A number of vegetation indices have been developed for broad-waveband optical sensors over the last three decades, and the following three vegetation indices have been used for the study of land surface phenology: Normalized Difference Vegetation Index (NDVI; Tucker 1979), Enhanced Vegetation Index (EVI; Huete et al. 1997) and Land Surface Water Index (LSWI; Xiao et al. 2002b).

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \tag{2}$$

$$EVI = 2.5 \times \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + 6 \times \rho_{red} - 7.5 \times \rho_{blue} + 1} \tag{3}$$

$$LSWI = \frac{\rho_{nir} - \rho_{swir}}{\rho_{nir} + \rho_{swir}} \tag{4}$$

For MODIS data, surface reflectance values from blue, red, NIR (841–875 nm), $SWIR1_1$ (1,628–1,652 nm) are used in calculation of NDVI, EVI and LSWI.

NDVI is calculated as the normalized ratio between NIR and red bands (Tucker 1979). Numerous studies have shown that NDVI is closely correlated with leaf area index (LAI), a biophysical parameter of the vegetation canopy (Gao et al. 2000). Fraction of photosynthetically active radiation absorbed by vegetation canopy (FAPARcanopy) is also assumed to be a linear or non-linear function of NDVI (Potter et al. 1993; Myneni and Williams 1994; Ruimy et al. 1994; Prince and Goward 1995; Justice et al. 1998). The LAI–NDVI relationship and NDVI–FAPAR relationship (Knyazikhin et al. 1998; Myneni et al. 2002) were developed largely from analysis of images from the AVHRR sensor onboard NOAA meteorological satellites, and are also used in the standard LAI/FAPAR product (MOD15A2; Myneni et al. 2002) from the MODIS sensor onboard the Terra satellite. The empirical relationships among LAI–NDVI–FAPAR are the dominant paradigm and the foundation for a number of satellite-based Production Efficiency model (PEM) that estimate gross primary production (GPP) or net primary production (NPP) of terrestrial ecosystems at the global scale (Potter et al. 1993; Ruimy et al. 1994; Prince and Goward 1995; Justice et al. 1998).

EVI is calculated from red, NIR and blue bands. An earlier study that used airborne multispectral data has shown that EVI is linearly correlated with the green leaf area index (LAIgreen) in crop fields (Boegh et al. 2002). Evaluation of radiometric and biophysical performance of EVI calculated from MODIS data indicated that EVI remain sensitive to canopy variation (Huete et al. 2002). In another study that compared NDVI and EVI data derived VGT images for Northern Asia over the period of 1998–2001, the results indicated EVI is less sensitive to residual atmospheric contamination due to aerosols from extensive fire in 1998 (Xiao et al. 2003).

LSWI is calculated as the normalized ratio between NIR and SWIR bands (Xiao et al. 2002b). As SWIR band is sensitive to leaf water content, a number of studies have explored the SWIR spectral bands (e.g. 1.6 and 2.1 mm) for vegetation water content (Hunt et al. 1987; Hunt and Rock 1989; Gao 1996; Serrano et al. 2000; Ceccato et al. 2001, 2002a, b; Xiao et al. 2002a, b; Roberts et al. 2003), and the results from these studies (Ceccato et al. 2002a, b) suggested that a combination of NIR and SWIR bands have the potential for retrieving leaf and canopy water content (equivalent water thickness, EWT, g cm^{-2}). A few water-oriented vegetation indices were developed for characterization of leaf and canopy water content, e.g. Moisture Stress Index (MSI; Hunt and Rock 1989), Normalized Difference Water Index (NDWI; Gao 1996), and Land Surface Water Index (LSWI; Xiao et al. 2002a, b). LSWI was previously called as the Normalized Difference Infrared Index (NDII; Hunt and Rock 1989), Very limited numbers of field studies on leaf water content have been carried out (Xiao et al. 2004a). Analysis of time series LSWI data have shown that LSWI is useful for improving land cover classification and phenology (Xiao et al. 2002a, b; Boles et al. 2004; Delbart et al. 2005; Sakamoto et al. 2007).

3 Land Surface Phenology of Forests, Grasslands and Cropland: Five Case Studies

In this section, we presented data from five CO_2 eddy flux tower sites, representing four vegetation types (deciduous broadleaf forest, evergreen needeleaf forest, temperate grassland, cropland, and evergreen tropical broadleaf forest). Time series data of vegetation indices (NDVI, EVI and LSWI) were compared with NEE and GPP data from the tower sites.

3.1 Land Surface Phenology of Temperate Deciduous Broadleaf Forests

Here we present CO_2 eddy flux data and satellite images for two eddy flux tower sites in USA and China as case studies that use CO_2 flux data for interpreting phenology (spring and fall) of multi-temporal satellite images at moderate spatial resolution.

3.1.1 Harvard Forest (USA)

The eddy flux tower site (42.54°N, 72.18°W, 340 m elevation) is located within Harvard Forest, Petersham, Massachusetts, USA. Vegetation at the site is primarily a 60–80-year-old deciduous broadleaf forest, and dominant species composition includes red oak (*Quercus rubra*), red maple (*Acer rubrum*), black birch (*Betula lenta*), white pine (*Pinus strobes*) and hemlock (*Tsuga Canadensis*). Annual mean temperature is about 7.9°C and annual precipitation is about 1,066 mm. On the average, plant growing season lasts for 161 days (Waring et al. 1995).

Eddy flux measurements of CO_2, H_2O and energy at Harvard Forest have been collected since 1991 (Wofsy et al. 1993; Goulden et al. 1996; Barford et al. 2001). Daily data of maximum and minimum temperature (°C), precipitation (mm) and photosynthetically active radiation (PAR, mol m^{-2} d^{-1}) in 2000 were obtained from the website of Harvard Forest (http://www-as.harvard.edu/data/nigec-data.html). Daily measured NEE flux data and derived GPP and ecosystem respiration (Reco) at Harvard Forest in 2000 were provided by researchers at Harvard Forest. Daily climate and CO_2 flux data were aggregated to the 10-day interval as defined by the 10-day composite VGT images (days 1–10, 11–20, and 21 to the end of the month).

We acquired the VGT-S10 data (http://free.vgt.vito.be) over the period of January 1–10, 2000 to December 21–31, 2000 (a time-series data of 36 VGT-S10 images) for the study site. Three vegetation indices (NDVI, EVI and LSWI) were calculated for all the 10-day composite images (VGT-S10). A detailed description of the pre-processing and calculation of vegetation indices from VGT-S10 data can be found in (Xiao et al. 2003).

Figure 1 shows the seasonal cycle of NEE and GPP in 2000 at Harvard Forest. The CUP lasts from early May to early October, whereas PAP is from late March to late October (Fig. 1). GPP values were near zero in winter season (December, January, and February), because the deciduous dominated canopy is bare and low air temperature and frozen soil inhibit photosynthetic activities of conifer trees. GPP began to increase

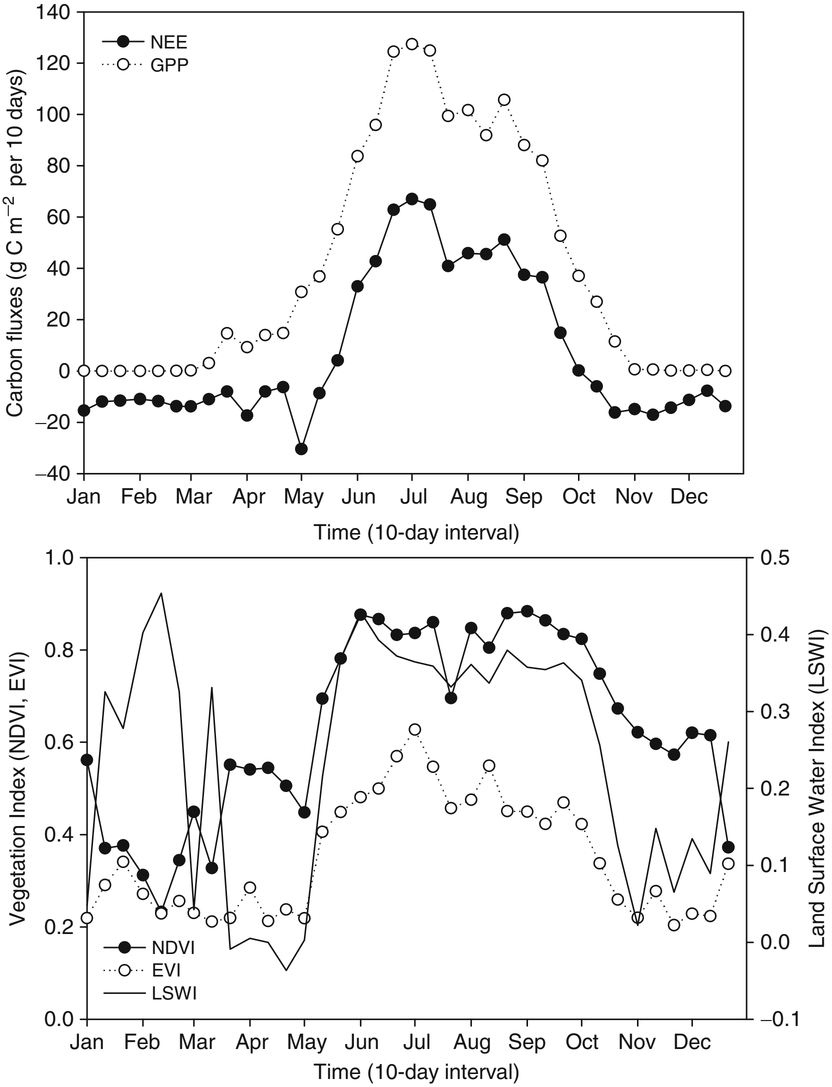

Fig. 1 Seasonal dynamics of net ecosystem exchange (NEE) of CO_2, gross primary production (GPP), Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI), and Land Surface Water Index (LSWI) in 2000 at the eddy flux tower in Harvard Forest, Massachusetts, USA. Here we used 10-day composites of VEGETASTION land surface reflectance data (VGT-S10).

in late March (mostly attributed to leaves of understory plants) and rose rapidly in late April to early Mary (mostly attributed to leaf emergence and expansion of upper canopy plants). GPP declined rapidly after its peak in late June to early July, despite that the fact that LAI changed little over the period between July and September.

The time series of LSWI data have a distinct seasonal cycle with a spring trough and a fall trough (Fig. 1). The high LSWI values in late fall, winter and early spring are attributed to snow cover (above or below the canopy). The green-up period (from bud burst to full expansion of leaves) is defined as the period from the date that had the minimum LSWI in spring to the date that had the maximum LSWI in early summer (early June at Harvard Forest site). Therefore, the plant growing season can be simply delineated as the period from the spring trough to the fall trough (Fig. 1). This LSWI-based delineation of plant growing season was first proposed in an early study of forests in Northern China (Xiao et al. 2002b), and late used in the study of forests in Russia (Delbart et al. 2005).

The time series of EVI data also have a distinct seasonal cycle (Fig. 1). The rapid increase of EVI in late April to early May also makes it relatively easy to define the starting dates of plant growing season.

The seasonal dynamic of NDVI (Fig. 1), particularly in the spring, is not as distinct as EVI and LSWI time series data. Note that NDVI has been widely used to delineate plant growing season; and a number of studies used a NDVI threshold value (Myneni et al. 1998; Jenkins et al. 2002). It is a reasonable choice and approach when NDVI data from AVHRR sensors were analyzed, as AVHRR sensors have only red and NIR bands. The NDVI-based threshold approach for delineating plant growing season (starting and ending dates of plant growing season) is clearly constrained by what threshold NDVI values to be used (White and Nemani 2006), as it might vary depending upon NDVI datasets generated by different research groups, vegetation types and vegetation conditions. For example, a threshold of 0.25 NDVI value from a AVHRR dataset was used to define plant growing season in the northern latitudes (Myneni et al. 1998), but a threshold of 0.45 NDVI value was used for eastern USA (Jenkins et al. 2002).

3.1.2 Changbai Mountain (China)

The CO_2 eddy flux tower site (42.40°N, 128.10°E) is located within No. 1 Plot of the Changbai Mountains Forest Ecosystem Research Station (CBM-FERS), Jilin Province, China. The CBM-FERS is one of Chinese Ecosystem Research Network (CERN) stations, Chinese Academy of Sciences. The climate belongs to the temperate continental climate influenced by monsoon, with four distinct seasons: windy spring, hot and rainy summer, cool autumn and cold winter. Annual mean temperature of the flux site ranges from 0.9 to 4.0°C and mean annual precipitation is 695 mm y^{-1} (1982–2004). The site has a flat topography, and the soil is classified as dark brown forest soil originating from volcanic ashes. The site is covered by on average 200-year-old, multi-layered, uneven-aged, multi-species mixed forest consisting of *Pinus koraiensis*, *Tilia amurensis*, *Acer mono*, *Fraxinus mandshurica*, *Quercus mongolica* and 135 other species. The mean canopy height is 26 m. A dense understory, consisting of broad-leaved shrubs, has a height of 0.5–2 m. The peak LAI is ~6.1 m^2 m^{-2}. CO_2 flux measurements at the site started in August 2002.

Figure 2 shows the seasonality of NEE and GPP at the Changbai site in 2003. The CUP ranges from early May to mid September, whereas PAP ranges from early April to late October.

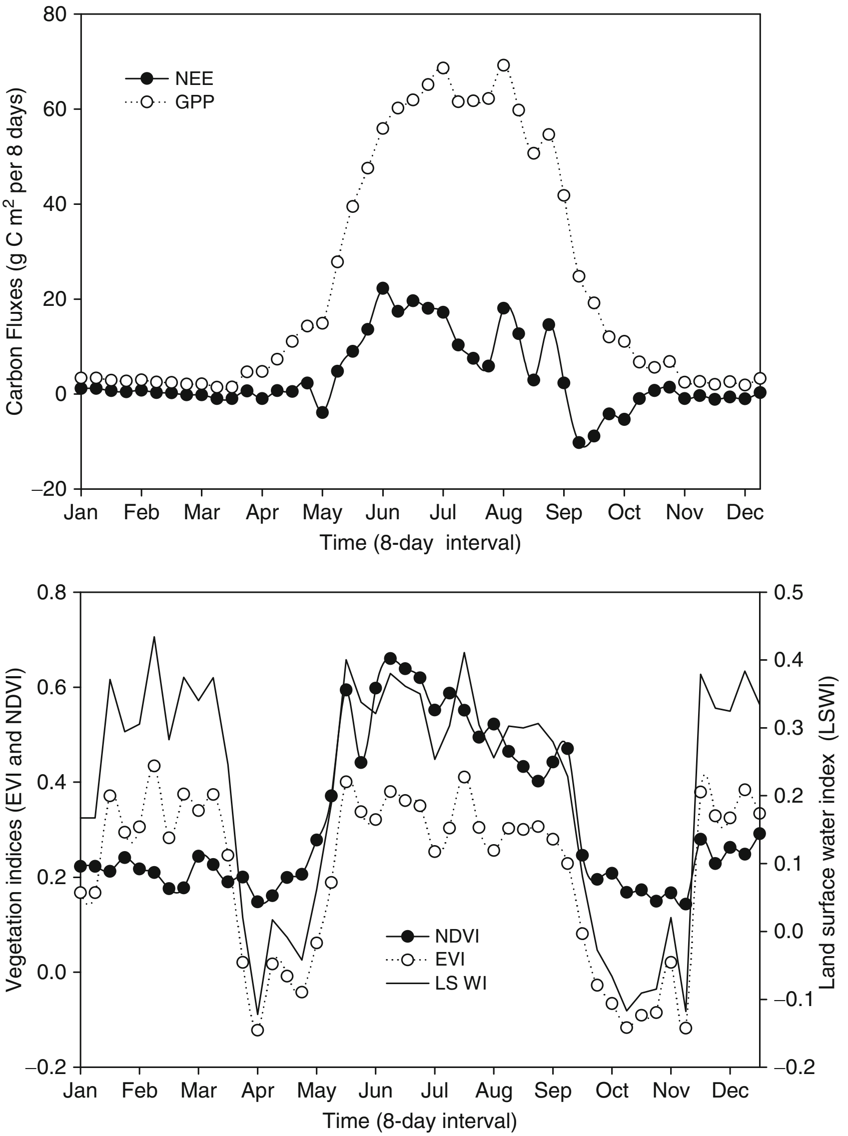

Fig. 2 Seasonal dynamics of net ecosystem exchange (NEE) of CO_2, gross primary production (GPP), Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI), and Land Surface Water Index (LSWI) in 2003 at the eddy flux tower in Changbain Mountain, Jilin province, China. Here we used 8-day composites of MODIS land surface reflectance product (MOD09A1).

Both LSWI and EVI time series data have distinct seasonal cycles with a spring trough and a fall trough (Fig. 2). LSWI values remained high during January to late February due to snow cover in the ground and canopy, but started to decline rapidly in March. After snowmelt in late March, EVI and LSWI values started to rise rapidly, corresponding well with the increases of GPP in early April (Fig. 2). In the fall season, both LSWI and EVI reached the lowest values by late October, corresponding well with the end of the photosynthetically active period. In comparison, NDVI reaches its lowest value in early November. Visual analysis of these three vegetation indices suggests that phenology of deciduous forests at this site can be also simply derived from the spring trough and fall trough of LSWI (Fig. 2).

3.2 Land Surface Phenology of Evergreen Needleleaf Forest

We used field data collected at an eddy flux tower site (45.20°N, 68.74°W) in Howland Forest, Maine, USA, where evergreen coniferous trees dominate (Hollinger et al. 1999). The vegetation of this 90-year-old evergreen needleleaf forest is about 41% red spruce (*Pinus rubens* Sarg), 25% eastern hemlock (*Tsuga canadensis* (L.) Carr.), 23% other conifers and 11% hardwoods (Hollinger et al. 1999). The peak LAI of the forest stand is approximately 5.3 $m^2\ m^{-2}$. Eddy flux measurements of CO_2, H_2O and energy at the site have being conducted since 1996 (Hollinger et al. 1999, 2004) and the site is part of the AmeriFlux network (http://public.ornl.gov/ameriflux/).

Both NEE and GPP time series data have distinct and consistent seasonal dynamics during 1998–2001 (Fig. 3). The flux tower site is carbon source throughout the winter season (November to March). GPP started to increase in late March and reached its peak values in late July to early August.

The low NDVI values in January–February are largely attributed to snow cover in the site (Fig. 3). NDVI time series data over a year does not show clear signal of seasonal dynamics in a year, which is to large degree attributed to saturation of NDVI in a forest with relatively high value of LAI. In contrast, EVI time series data have a distinct seasonal dynamics (Fig. 3).

The seasonal dynamics of LSWI is unique and characterized by a "spring trough" and a "fall trough." The high LSWI values in winter and early spring are attributed to snow cover in the forest stands. As snow melted in late March, LSWI declined. The "spring trough" corresponds to the beginning of photosynthetically active period of evergreen needleleaf forest, and the "fall trough" corresponds to the end of photosynthetically active period (Xiao et al. 2004a).

3.3 Land Surface Phenology of Temperate Grassland

The CO_2 eddy flux tower site (43.55°N, 116.68°E) of grassland is located within the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) in Xilingol

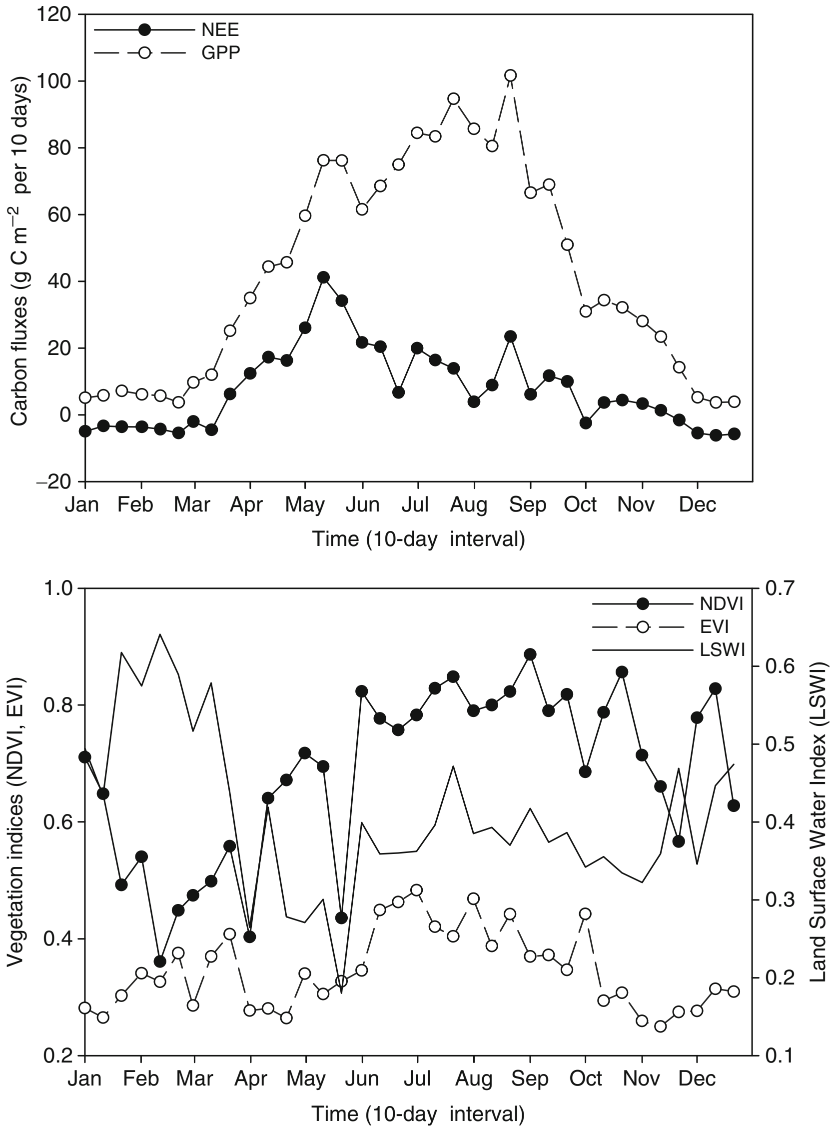

Fig. 3 Seasonal dynamics of net ecosystem exchange (NEE) of CO_2, gross primary production (GPP) of CO_2, Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI), and Land Surface Water Index (LSWI) in 2000 at the eddy flux tower in Howland, Maine, USA. Here we used 10-day composites of VEGETASTION land surface reflectance data (VGT-S10).

League, Inner Mongolia, China (Fu et al. 2006a, b). The IMGERS is one of the Chinese Ecosystem Research Network (CERN), Chinese Academy of Sciences. The study area has flat topography with an elevation of 1,000 m. Annual mean precipitation is approximately 350.9 mm, with more than 80% of precipitation occurring in the peak plant growing season of July and August. The growing season is generally short because much of the region is snow-covered from late October to early April. The mean annual temperature is approximately −0.4°C; the mean temperature of the coldest month (January) is −19.5°C; and the mean temperature of the warmest month (July) is 20.8°C. The dominant species of Xilingol grassland include *Leymus Chinensis*, *Achnatherum sibiricum*, *Stipa gigantean* and *Agropyron michnoi* (Xiao et al. 1995, 1996). Major soil type is chestnut soil with about 3% organic matter. Flux measurements of CO_2, H_2O and energy at the tower site started on April 23, 2003 (Fu et al. 2006a).

Figure 4 shows the seasonal dynamics of NEE and GPP in 2004. GPP started to increase in early May, and ended in late September. The plant growing season in 2004, defined as the carbon uptake period, was from early May to late September.

LSWI values were high in February and March, and declined rapidly in late March due to snowmelt. Right after snowmelt, NDVI experienced the first increase from early March (NDVI = 0.1) to late March (NDVI = 0.2), which illustrates the sensitivity of NDVI to soil moisture, as wet soils resulted in higher NDVI values. Note that both EVI and NDVI started to increase in late April to early May, corresponding well with the increase of GEE in early May. Evidently, one can use those dates with consistent increases of vegetation indices (NDVI, EVI and LSWI) in spring after snowmelt as the starting date of the plant growing season. LSWI values reached its lowest value in late September, corresponding well with the ending dates of the carbon uptake period. While one can still use a threshold of NDVI or EVI to define the ending date of the plant growing season, LSWI seems to offer a clean and simple alternative approach to delineate the ending dates of the plant growing season.

3.4 Land Surface Phenology of Croplands: Wheat and Corn Fields

The eddy flux tower site (36.95°N, 116.60°E, 28 m elevation) is located in Yucheng County, Shandong Province, China. The study site has a crop rotation of winter wheat and maize in a year. Annual mean temperature at this site is about 13.1°C and annual precipitation is approximately 528 mm. On the average, mean annual sunshine duration is about 2,640 h and frost-free period is about 200 days.

Eddy flux measurement system were located in the center of a crop field within a large and homogeneous cropland area, and CO_2, H_2O and energy fluxes have been simultaneously measured since 2003 (Li et al. 2006; Zhao et al. 2007). Daily data of maximum and minimum temperature (°C), precipitation (mm) and photosynthetically active radiation (PAR, mol m^{-2} d^{-1}) were also available from this site for this study.

Daily flux data of NEE, GPP and ecosystem respiration (Reco) at the flux sites were generated from the half-hourly flux data. Half-hourly values were calculated from the covariance of the fluctuations in vertical wind speed and CO_2 concentration

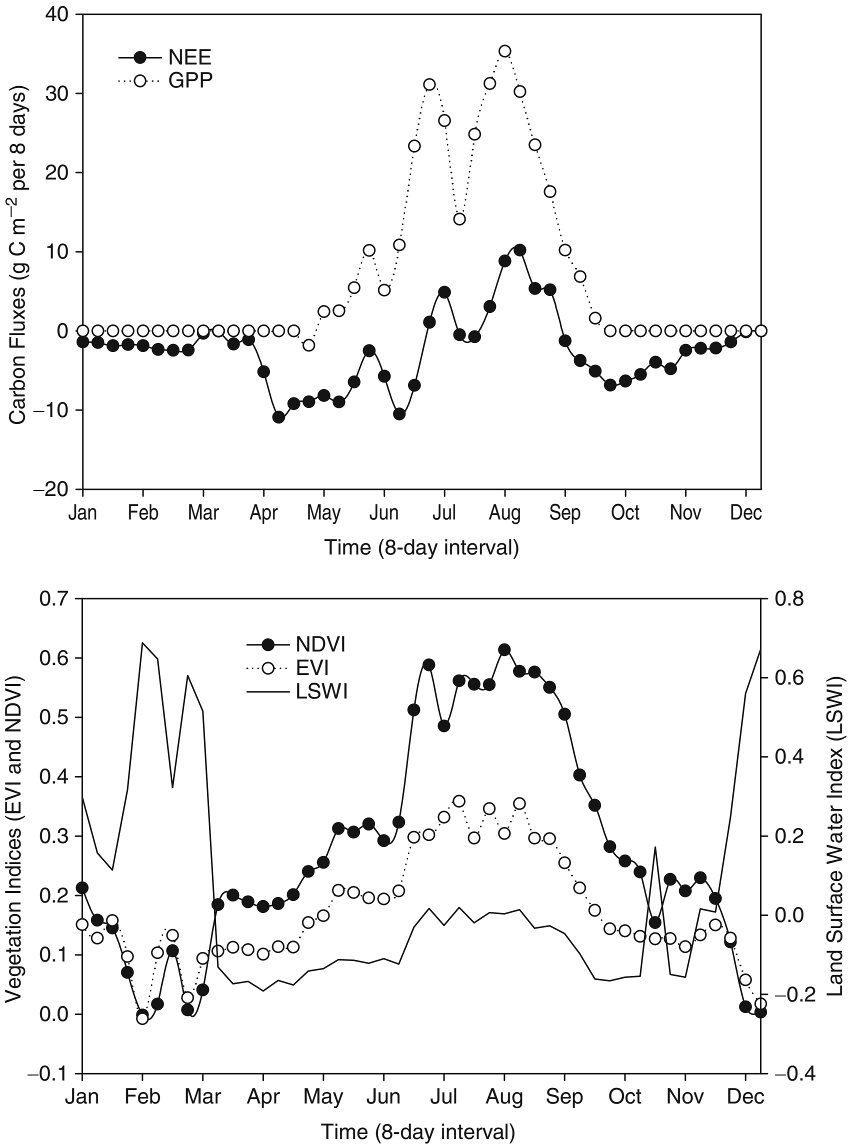

Fig. 4 Seasonal dynamics of net ecosystem exchange (NEE) of CO_2, gross primary production (GPP), Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI), and Land Surface Water Index (LSWI) in 2004 at the eddy flux tower of grassland ecosystem in Xilingol, Inner Mongolia, China. Here we used 8-day composites of MODIS land surface reflectance product (MOD09A1).

measured at 5 Hz. We calculated the 8-day sums of GPP and NEE from the daily GPP and NEE data, in order to be consistent with the 8-day composite satellite images we used.

Figure 5 shows that NEE and GPP time series had two distinct crop growth cycles, corresponding to the rotation of winter wheat and maize crops in a year. For winter wheat crop, which were planted in previous year (fall of 2002), GPP values

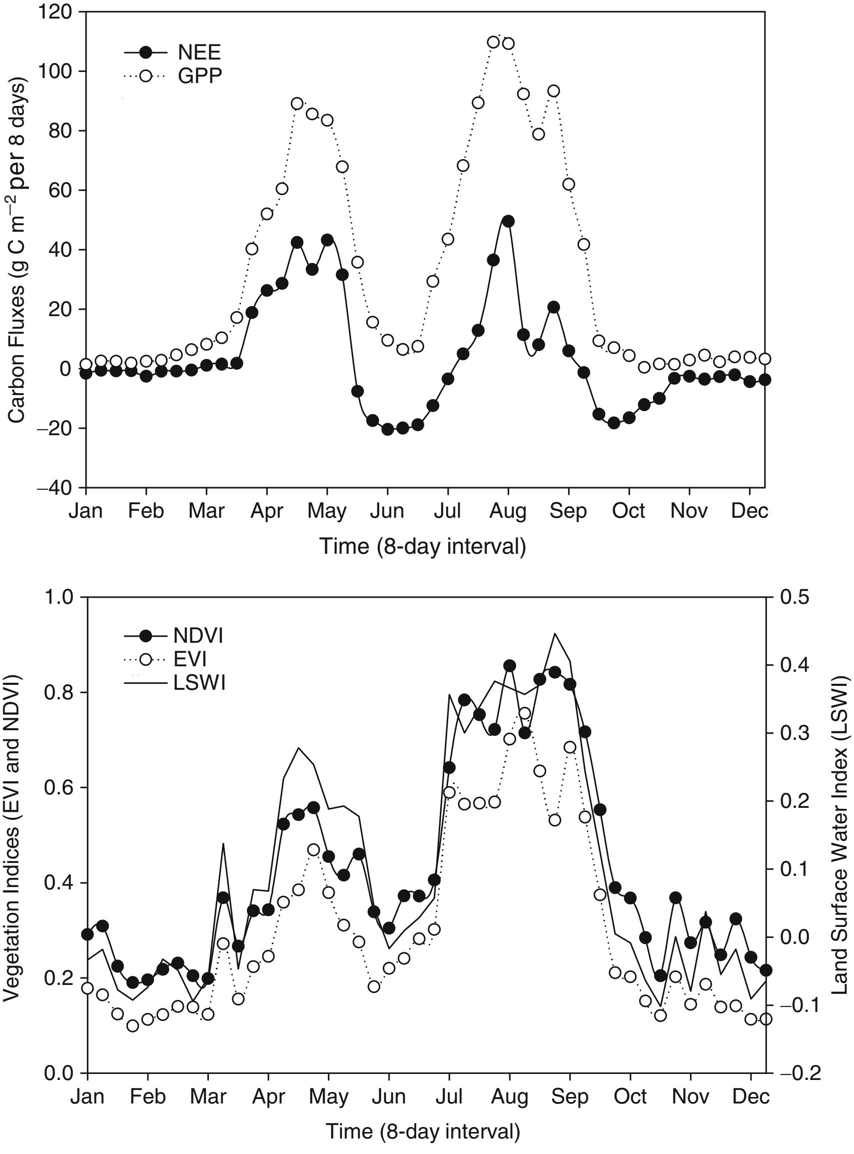

Fig. 5 Seasonal dynamics of net ecosystem exchange (NEE) of CO_2, gross primary production (GPP), Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI), and Land Surface Water Index (LSWI) in 2004 at the eddy flux tower of croplands in Yuchen, Hebei province, China. Here we used 8-day composites of MODIS land surface reflectance product (MOD09A1).

were close to zero during January to February, and started to increase by March, as air temperature increased in spring. Winter wheat crop reached its maximum GPP value (~89 g C m^{-2} 8 d^{-1}) by late April and then declined gradually. By early June winter wheat was harvested. Within 2-weeks after the harvest of winter wheat, summer maize crops were planted. For maize crops, GPP values increased rapidly and reached its maximum values (~103 g C m^{-2} 8 d^{-1}) by early August. Maize crops were harvested in early October. For this cropland site, the CUP has little difference from the PAP (Fig. 5).

NDVI, EVI and LSWI time series data all have bimodal temporal curves, corresponding to the rotation of winter wheat – maize crops. For the first cycle, both NDVI and EVI values started to increase by early March as winter wheat plants turn green, and reached a plateau by late April. After the harvest of winter wheat in early June, both NDVI and EVI values dropped. The timing of NDVI and EVI dynamics for winter wheat is consistent with the phenological or seasonal cycle of winter wheat. For the second cycle, both NDVI and EVI started to substantially increase by early July, corresponding to the planting of summer maize crop. After the harvest of maize in late September, both NDVI and EVI values dropped substantially.

3.5 Land Surface Phenology of Seasonally Moist Tropical Evergreen Broadleaf Forest

The CO_2 eddy flux tower site (2.85°S, 54.97°W) is located in the Tapajos National Forest, south of Santarem, Para, Brazil. It is an old-growth, seasonally wet tropical evergreen forest. Annual precipitation is approximately 1,920 mm with distinct wet and dry seasons. The 7-month wet season is usually from December through June, and the dry season is from July to November. Continuous measurement of CO_2, H_2O and energy fluxes at the site has been conducted since April 2001.

The analysis of CO_2 flux data at the site reported that this site maintained high gross primary production during the dry season (Saleska et al. 2003). The observed H_2O flux data at the flux tower site show that the evapotranspiration at the site was higher in dry season than in wet season (Fig. 6). It was proposed that seasonally moist tropical evergreen forest have evolved two adaptive mechanisms in an environment with strong seasonal variation of light and water (1) deep root system to access water from deep soils, and (2) leaf phenology for maximum utilization of light (Xiao et al. 2005).

EVI values increased gradually from July to November (Fig. 6), representing a canopy dynamic process within the dry season. This EVI dynamics is temporally consistent with two processes that occur in the canopy during the dry season (1) fall of old leaves in the canopy at the early dry season and (2) emergence of new leaves in the late dry season (Xiao et al. 2005). In comparison, NDVI time series data from the MODIS sensor have low values in wet season (from January to June), mostly due to atmospheric condition (e.g. thin clouds), but remain similar high values in

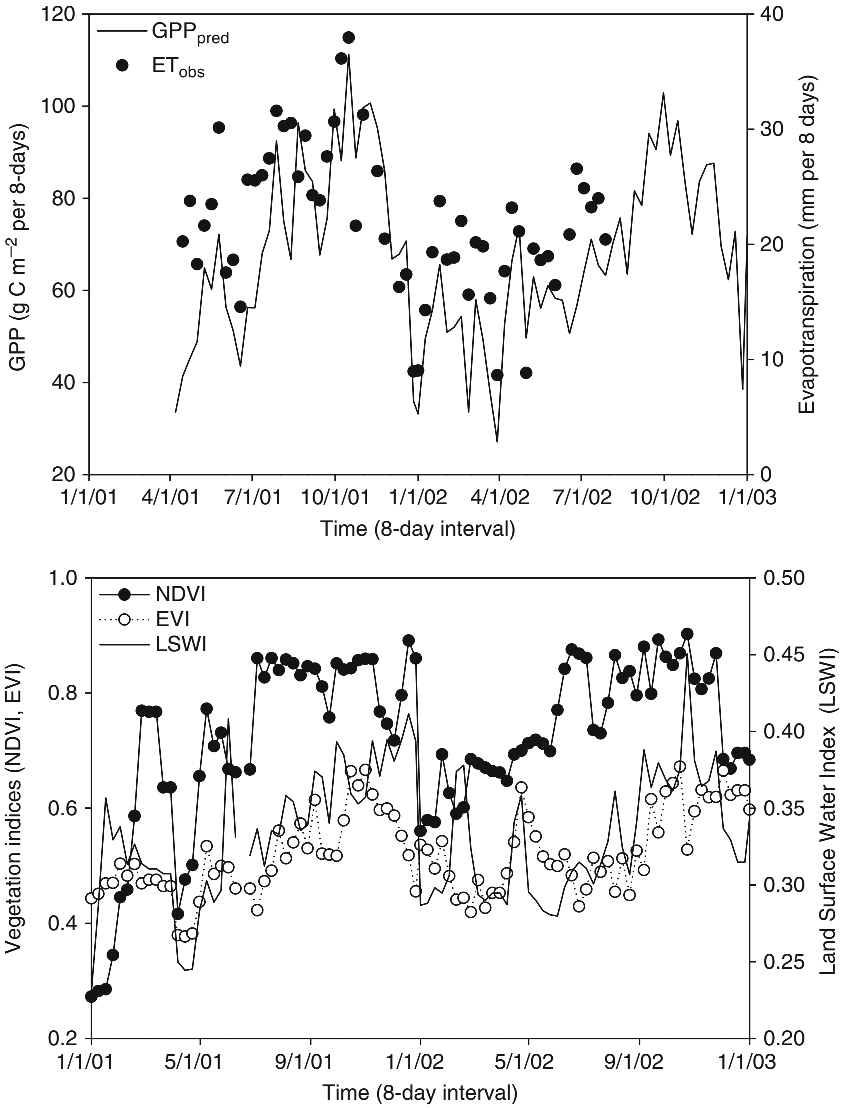

Fig. 6 Seasonal dynamics of observed evapotranspiration, predicted gross primary production from a model (Xiao et al. 2005), Enhanced Vegetation Index (EVI), Normalized Difference Vegetation Index (NDVI), and Land Surface Water Index (LSWI) in 2001–2002 at the eddy flux tower of evergreen tropical forest in Tapajos, Brazil. Here we used 8-day composites of MODIS land surface reflectance product (MOD09A1).

dry season from June to November, which shows no temporal dynamics in dry season (Fig. 6). Mature evergreen tropical forests usually have high LAI (>4 m^2 m^{-2}), which results in saturation of NDVI. The high LAI also presents challenges for phenological studies. Consequently, there are a limited number of field-based phenological studies for evergreen forests in tropical South America (Van Schaik et al. 1993; Wright and van Schaik 1994).

The long-held and conventional wisdom has been that mature evergreen tropical forests have a monotonous growing season, in other words, there is no seasonal dynamics of leaf phenology in evergreen tropical forests. This conventional wisdom was recently challenged by eddy flux data (Saleska et al. 2003) and analysis of EVI and LSWI data from Vegetation and MODIS sensors (Xiao et al. 2005) at a seasonally moist evergreen tropical forest site. Recent analyses of EVI data over the Amazon basin further suggest that there is large seasonal dynamics of leaf phenology in mature forests in the Amazon basin (Huete et al. 2006; Xiao et al. 2006).

4 Summary

Phenology of plants has been studied from several perspectives, including in-situ observations of leaf and flowering, bio-climate, eco-physiology and satellite observation. The eco-physiological approach focuses on continuous data from CO_2 eddy flux tower sites. Year-long continuous CO_2 flux data from the eddy flux tower sites enable the scientific community to delineate the carbon uptake period (CUP), which is defined by net ecosystem exchange (NEE) of CO_2 between the terrestrial ecosystems and the atmosphere, and the photosynthetically active period (PAP), which is defined by gross primary production (GPP). To what degree will the photosynthetically active period (PAP) as delineated by GPP be consistent with the phenology as delineated by satellite observations? Which vegetation index is better to delineate land surface phenology (land surface dynamics in spring and fall)? Can several vegetation indices be used together to improve delineation of land surface phenology? Will phenology delineated from eco-physiological approach and satellite observation approach be consistent with the phenology delineated from the bio-climatic approach and in-situ observations (scaling-up from in-situ individual plants to landscapes)? The case studies presented in this chapter provide exploratory data analyses that compare CO_2 flux data (NEE and GPP) with vegetation indices, which shed new lights on the questions mentioned above.

Among the three vegetation indices (NDVI, EVI and LSWI) we discussed in this chapter, NDVI has the longest time series data (from early 1980s to present), and is most widely used and well documented in the literature. Time series of NDVI data is useful for delineating land surface phenology, Careful comparisons between NDVI and CO_2 flux data, as reported in this chapter, highlights the limitation and problems of NDVI for land surface phenology, in particular for forests with large values of leaf area index. One can still use a threshold of NDVI or EVI to define the beginning and ending date of the plant growing season, however LSWI seems to offer a clean and simple alternative approach to delineate the ending dates of the plant growing season.

LSWI and EVI time series data together have shown distinct seasonal cycles with a spring trough and a fall trough. The increases of the EVI and LSWI values have shown strong relationship with the increases of GPP. Both EVI and LSWI provide new and complementary data to delineate land surface phenology, and they are clearly more consistent with the CO_2 flux data than does NDVI in forest ecosystems.

Accuracy assessment and validation of land surface phenology is a long-term effort that requires coordination from both the remote sensing community and the CO_2 eddy flux community. At present, there are more than 600 CO_2 eddy flux tower sites across various biomes in the world, including different land use, management, disturbance stages. The eddy flux community needs to partition half-hourly NEE data into GPP and ecosystem respiration in a consistent method, and provide GPP data to users in a timely fashion. The remote sensing community needs to provide time series data of vegetation indices for the eddy flux tower sites in a timely fashion, including daily satellite images. In addition, the scientific community also needs to facilitate integration of other in situ field observations (e.g. leaf emergence and leaf fall, canopy dynamics as observed from web cameras) with CO_2 fluxes and remote sensing data. The advance of internet, computer and web technology makes it possible for the scientific community to develop a citizen-based network of plant phenology through participation of individual citizens and scientists, which would offer the capacity of near-real time monitoring of land surface phenology.

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