Remote Sensing of Environment 174 (2016) 290–300

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Matching the phenology of Net Ecosystem Exchange and vegetation indices estimated with MODIS and FLUXNET in-situ observations

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ARTICLE INFO

Article history:
Received 22 April 2015
Received in revised form 10 December 2015
Accepted 11 December 2015
Available online xxxx

Keywords:
Vegetation indices (VI's)
Net Ecosystem Exchange (NEE)
Start of net carbon uptake (SGS_{NEE})
Start of growing season (SGS)
Plant functional types (PFT's)
Phenology

ABSTRACT

Shifts in ecosystem phenology play an important role in the definition of inter-annual variability of net ecosystem carbon uptake. A good estimate at the global scale of ecosystem phenology, mainly that of photosynthesis or gross primary productivity (GPP), may be provided by vegetation indices derived from MODIS satellite image data.

However, the relationship between the start date of a growing (or greening) season (SGS) when derived from different vegetation indices (VI's), and the starting day of carbon uptake is not well elucidated. Additionally, the validation of existing phenology data with in-situ measurements is largely missing. We have investigated the possibility to use different VI's to predict the starting day of the growing season for 28 FLUXNET sites as well as MODIS data. This analysis included main plant functional types (PFT's).

Of all VI's taken into account in this paper, the NDVI (Normalized Difference Vegetation Index) shows the highest correlation coefficient for the relationship between the starting day of the growing season as observed with MODIS and in-situ observations. However, MODIS observations elicit a 20–21 days earlier SGS date compared to in-situ observations. The prediction for the NEE start of the growing season diverges when using different VI's, and seems to depend on the amplitude for carbon and VI and on PFT. The optimal VI for estimation of a SGS date was PFT-specific — for example the WRDVI for cropland, but the MODIS NDVI performed best when applied as an estimator for Net Ecosystem Exchange and when considering all PFT's pooled.

1. Introduction

Ecosystem phenology shifts play an important role in describing the inter-annual variability of NEE (Net Ecosystem Exchange) due to its impact on gross primary productivity (GPP). A shift in the start date of a growing season modulates annual GPP (Churkina et al., 2005; Keenan et al., 2014; Richardson et al., 2010). Multiple data sources – primarily carbon dioxide (CO_2) eddy covariance flux data (NEE) as well as satellite imagery estimated vegetation indices (VI's) – originating from different databases are used to estimate the start day of a growing season (Garrity et al., 2011).

GPP and NEE seasonality is frequently defined as carbon-flux phenology. Both variables describe the seasonality of ecosystem gross photosynthesis. Photosynthetic phenology is represented by the starting day of GPP and NEE and more specifically when NEE becomes positive. Explicitly the date when this occurs is by definition the day (SGS_{NEE}) when an ecosystem transforms from a carbon source into a carbon sink. SGS_{NEE} can be estimated in different ways. Eddy covariance data is on track to make the estimate (Baldocchi et al., 2005). On the other hand, leaf phenology can also be observed and defined with remote sensing based methods (Garrity et al., 2011). The exercise is to estimate the starting day of greening (SGS_{MODIS} and $SGS_{in\text{-}situ}$) using an optical sensor (MODIS or in-situ). Intuitively, this is expected to correspond to SGS_{NEE}, but this relationship, and hence the predictability of SGS_{NEE} from optical sensors, has yet to be verified. It is assumed in this paper that a correspondence with SGS_{NEE} exists. It is the objective of this

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http://dx.doi.org/10.1016/j.rse.2015.12.017
0034-4257/

paper to verify, even validate this correspondence and hence whether SGS_{NEE} can be estimated from a space remote sensing platform (TERRA MODIS).

Several studies highlight a new application of remote sensing i.e., the integration of remote sensing data as well as NEE and GPP data collected with the eddy covariance method, to predict and map terrestrial carbon assimilation at the global and regional scales (Heinsch et al., 2006; Verma et al., 2014). An important step in this research venture is to establish a correspondence between phenological data – observed with remote sensing – versus in-situ optical and eddy covariance flux data.

Remote sensing facilitates the global observation of the starting day of a growing season defined as the starting day of gross photosynthesis. Several approaches are applied to monitor changes in canopy development. These include changes in greening, acquired by digital camera imagery (Betancourt et al., 2005; Richardson et al., 2009), spectral spaces, reflectance and reflectance relationships (Nguy-Robertson et al., 2012) and vegetation indices (Wu, 2014; Zhang et al., 2003). The latter is a common approach and has been applied using proximal sensors, such as radiometers (Huemmrich et al., 1999) or modified cameras (Petach et al., 2014; Sakamoto et al., 2010), and satellite sensor imagery (Walker et al., 2014).

Several VI's are considered as a useful estimator of bio-geophysical and biochemical parameters regulating leaf and canopy phenology and hence, productivity. Typical bio-geophysical variables derived from remote sensing platforms are leaf area index (LAI) and chlorophyll a and b (Gitelson et al., 2006; Myneni et al., 2002). A great variety of VI's have been defined by remote sensing scientists and all differ in their definition and in their sensitivity to changes in photosynthesis as well. These so-called “Greenness indices” – such as the widely used Normalized Difference Vegetation Index (NDVI) (Tucker, 1979) – demonstrate to be a good proxy for the fraction of absorbed PAR (*f*APAR) and PAR is Photosynthetically Active Radiation and APAR is absorbed PAR. By definition, *f*APAR = APAR/PAR. Hence *f*APAR and the NDVI are related with green biomass and canopy structure. Furthermore, the NDVI has been recognized to be a good proxy for the investigation of the impact of climate change on leaf and ecosystem phenology (Peng et al., 2013; Piao et al., 2015).

In addition to the NDVI, many other vegetation indices have also been defined. Among many others one can cite: the Enhanced Vegetation Index (EVI) (Huete et al., 1997). Both the NDVI and EVI allow the observation of canopy greening based on their dependency on the RED and near infrared (NIR) parts of the electromagnetic spectrum (Huete et al., 2002; Piao et al., 2006; Reed et al., 1994). The EVI is generally less sensitive to soil background variations compared to other VI's when vegetation cover fraction (*f*Cover) is low (Huete et al., 2002). The EVI incorporates an additional blue spectral band in addition to the commonly used RED and NIR spectral bands. The use of a blue band is intended to reduce atmospheric scattering effects typically due to the interaction of — most strongly, blue — light with aerosols and atmospheric molecules. The EVI definition reduces noise, but its applicability is limited to those sensors which dispose of a blue band, which puts a limit on the number of satellite sensors which can be used for global studies.

Jiang et al. (2008) proposed an alternative definition for the EVI, e.g., the EVI2 in which the blue spectral band is substituted by a red band. Though EVI2 does not make use of a blue band, EVI2 has been determined to be equivalent to EVI and seems helpful to observe canopy properties. A benefit of EVI and EVI2 is that they remain more sensitive than the NDVI when canopies become denser. However, even these vegetation indices do saturate at moderate LAI values (Viña et al., 2011). Alternatively, the Wide Dynamic Range Vegetation Index (WDRVI) seems more sensitive for the entire dynamic range of the LAI (Gitelson, 2004). The Simple Ratio (SR) however has been shown to be the most sensitive VI at high LAI values (Viña et al., 2011).

The Global Environmental Monitoring Index (GEMI) has been defined based on RED and NIR band reflectances. GEMI minimizes atmospheric effects, similar to the EVI and minimizes observational angular effects as well (e.g. BRDF effects) in the observed VI signal (Pinty and Verstraete, 1992). Nevertheless GEMI is rarely used in canopy phenology observations.

The Soil Adjusted Vegetation index (SAVI) has been defined to minimize the influence of soil brightness (Huete, 1988). The SAVI involves the RED and NIR reflectance bands and a soil brightness correction factor (L). L equals zero for a very high vegetation cover and unity for non-vegetated land surfaces. Typically, L is assumed to be 0.5 for most vegetated areas. By definition SAVI equals the NDVI when L equals zero.

A variety of in-situ optical sensors are commercially available for field, UAV and airborne applications. They acquire NIR and RED band reflectances at top-of-the-canopy level (Balzarolo et al., 2011). PAR sensors can be applied as broadband sensors for reflectances in the visible spectral range. These data can then be used instead of RED band imagery, to calculate vegetation indices. Likewise, pyranometers are sensitive in the global shortwave radiation band (GLR) and they can be applied as a NIR sensitive reflectance band. GLR spans a broad spectral range, including the visible, NIR, and mid-infrared spectral regions. The visible spectral region in the GLR band can be brought to zero reflectance using the PAR sensor signal (Jenkins et al., 2007; Wang et al., 2004). With this approach in-situ NDVI can be derived from measurements of the PAR band (400–700 nm); and a visible corrected GLR band (700–2800 nm).

In-situ NDVI measurements provide distinct advantages. They are typically endowed with a high temporal resolution since they acquire data at an hourly basis and can be programmed for data collection at even higher frequencies. Important to mention is that in-situ NDVI measurements offer the possibility for data acquisition under overcast conditions. Only low altitude remote sensing systems like UAV's offer this capacity as well.

Finally, the objective of this paper is to explore the potential of six different VI's calculated from in-situ radiation measurements, and obtained from MODIS RED and NIR reflectances. This enables the estimation of the start of the carbon uptake season (i.e. SGS_{NEE}). Additionally the approach should also enable the phenological monitoring at twenty-eight different FLUXNET sites encompassing eight different PFT's (or ecosystems).

The specific objectives pursued in this paper are:

(1) How well do SGS estimations derived from in-situ vegetation indices (referred to as $SGS_{in\text{-}situ}$) correlate with SGS estimations derived from MODIS VI's (referred to as SGS_{MODIS}) and secondly;
(2) Which VI's as well as sensors are optimal for SGS_{NEE} detection based on in-situ NEE flux data collected at FLUXNET sites.

2. Materials and methods

2.1. FLUXNET data: site selection

The study presented in this paper is based on VI's, determined with remote sensing and carbon flux measurements acquired from the FLUXNET eddy covariance network (www.fluxdata.org, “La Thuile” database, October 2010). The FLUXNET database contains half-hourly observations of ecosystem CO_2, heat fluxes and meteorological data of more than 250 sites worldwide and for a total of 960 site-years. The most representative sites used in this study have been selected based on the following boundary conditions:

(1) The availability of continuous measurements of global incoming and outgoing shortwave radiation (GLR_{in} and GLR_{out}) respectively, since both are required to calculate in-situ VI's;
(2) The availability of continuous measurements of global incoming and outgoing PAR (PAR_{in}, PAR_{out}), since both are required to calculate in-situ VI's;