ARTICLE IN PRESS

Agricultural and Forest Meteorology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

NDVI derived from near-infrared-enabled digital cameras: Applicability across different plant functional types

Gianluca Filippa[a,*], Edoardo Cremonese[a], Mirco Migliavacca[b], Marta Galvagno[a], Oliver Sonnentag[c], Elyn Humphreys[d], Koen Hufkens[e], Youngryel Ryu[f], Joseph Verfaillie[g], Umberto Morra di Cella[a], Andrew D. Richardson[e]

[a] Environmental Protection Agency of Aosta Valley, ARPA Valle d'Aosta, Climate Change Unit, Italy
[b] Max Planck Institute for Biogeochemistry, Department Biogeochemical Integration, Jena, Germany
[c] Département de géographie & Centre d'études nordiques, Université de Montréal, Montréal, QC, Canada
[d] Department of Geography and Environmental Studies, Carleton University, Ottawa, ON, Canada
[e] Northern Arizona University School of Informatics Computing and Cyber Systems, Flagstaff, AZ, 86011, USA
[f] Department of Landscape Architecture and Rural Systems Engineering, Seoul National University, Republic of Korea
[g] Department of Environmental Science, Policy and Management, University of California, Berkeley, CA, USA

ARTICLE INFO

Keywords:
Camera NDVI
Color indices
Near-surface remote sensing
PhenoCam
Phenology
Phenopix

ABSTRACT

Time series of vegetation indices (e.g. normalized difference vegetation index [NDVI]) and color indices (e.g. green chromatic coordinate [G_{CC}]) based on radiometric measurements are now available at different spatial and temporal scales ranging from weekly satellite observations to sub-hourly *in situ* measurements by means of near-surface remote sensing (e.g. spectral sensors or digital cameras). *In situ* measurements are essential for providing validation data for satellite-derived vegetation indices. In this study we used a recently developed method to calculate NDVI from near-infrared (NIR) enabled digital cameras ($NDVI_C$) at 17 sites (for a total of 74 year-sites) encompassing six plant functional types (PFT) from the PhenoCam network.

The seasonality of $NDVI_C$ was comparable to both NDVI measured by ground spectral sensors and by the moderate resolution imaging spectroradiometer (MODIS). We calculated site- and PFT-specific scaling factors to correct $NDVI_C$ values and recommend the use of site-specific NDVI from MODIS in order to scale $NDVI_C$. We also compared G_{CC} extracted from red-green-blue images to $NDVI_C$ and found PFT-dependent systematic differences in their seasonalities. During senescence, $NDVI_C$ lags behind G_{CC} in deciduous broad-leaf forests and grasslands, suggesting that G_{CC} is more sensitive to changes in leaf color and $NDVI_C$ is more sensitive to changes in leaf area. In evergreen forests, $NDVI_C$ peaks later than G_{CC} in spring, probably tracking the processes of shoot elongation and new needle formation. Both G_{CC} and $NDVI_C$ can be used as validation tools for the MODIS Land Cover Dynamics Product (MCD12Q2) for deciduous broad-leaf spring phenology, whereas $NDVI_C$ is more comparable than G_{CC} with autumn phenology derived from MODIS. For evergreen forests, we found a poor relationship between MCD12Q2 and camera-derived phenology, highlighting the need for more work to better characterize the seasonality of both canopy structure and leaf biochemistry in those ecosystems.

Our results demonstrate that $NDVI_C$ is in excellent agreement with NDVI obtained from spectral measurements, and that $NDVI_C$ and G_{CC} can complement each other in describing ecosystem phenology. Additionally, $NDVI_C$ allows the detection of structural changes in the canopy that cannot be detected by visible-wavelength imagery.

1. Introduction

Vegetation phenology (the study of the timing of recurrent biological events) is highly sensitive to climate variability and change (Rosenzweig et al., 2007; Migliavacca et al., 2012; Richardson et al., 2013). Phenological time-series based on radiometric measurements are now available, covering different spatial and temporal scales ranging from weekly satellite observations to sub-hourly *in situ* measurements by means of, e.g. spectral sensors or digital repeat photography. Regarding satellite-based data, the trade-off between spatial and temporal resolution represents a critical limitation especially in heterogeneous, fragmented ecosystems. To overcome this limitation, and in

* Corresponding author.
E-mail address: gian.filippa@gmail.com (G. Filippa).

https://doi.org/10.1016/j.agrformet.2017.11.003
Received 11 April 2017; Received in revised form 31 August 2017; Accepted 4 November 2017

Table 1
Study site locations along with PhenoCam and Fluxnet site IDs, plant functional types (PFT) and years of data analyzed. PFT are as follows: CRO, croplands; DBF, deciduous broad-leaf forests; ENF, evergreen needle-leaf forests; GRA, grasslands; SHB, shrublands. Note that PFT are defined according to the vegetation that characterizes the chosen regions-of-interest. They do not necessarily match the PFT classification for the whole site. Asterisks denote sites where light-emitting diode (LED) sensors were also available.

PhenoCam ID	Fluxnet ID	Coords (lat, long)	Years	PFT	Reference
southerngreatplains	US-ARM	36.7, −97.5	2012–2015	CRO	Fischer et al. (2007)
bartlett*	US-Bar	44.1, −71.3	2010–2015	DBF	Richardson et al. (2007)
harvardbarn2*	US-Ha1	42.5, −72.2	2012–2015	DBF/ENF	Magill et al. (2004)
willowcreek	US-WCr	45.8, −90.1	2012–2015	DBF	Cook et al. (2004)
freemanwood	US-FR3	29.9, −98.0	2012–2013	DBF	Heinsch et al. (2004)
alligatoriver	US-NC4	35.8, −75.9	2013–2015	DBF	www.fws.gov/refuge/Alligator_River/
turkeypointenf39	CA-TP4	42.7, −80.4	2012–2015	ENF	Arain and Restrepo-Coupe (2005)
oregonMP		44.5, −121.6	2012–2015	ENF	Thomas et al. (2009)
vaira*	US-Var	38.4, −121.0	2011–2015	GRA	Baldocchi et al. (2004)
lethbridge	CA-Let	49.7, −112.9	2011–2015	GRA	Flanagan et al. (2002)
tonzi*	US-Ton	38.4, −121.0	2011–2015	DBF/GRA	Baldocchi et al. (2004)
ibp		32.6, −106.8	2014–2015	GRA	Havstad et al. (2000)
canadaOBS	CA-Obs	54.0, −105.1	2011–2015	MF	Gower et al. (1997)
merbleue*	CA-Mer	45.4, −75.5	2012–2015	SHB	Sonnentag et al. (2007)
luckyhills	US-Whs	31.7, −110.1	2014–2015	SHB	Emmerich (2003)
jernort		32.6, −106.8	2014–2015	SHB	Emmerich (2003)
burnssagebrush	US-Bsg	43.5, −119.7	2012–2015	SHB	oregonstate.edu/dept/eoarc/

the attempt to fill the gap between point and landscape-level observations, the use of near-surface remote sensing has been notably growing in the last 20 years (Brown et al., 2016). In this context, digital repeat photography (e.g. Richardson et al., 2007, 2009; Sonnentag et al., 2012) is an attractive option because images can be analyzed either qualitatively or quantitatively (Kosmala et al., 2016), and analyses can focus on individual organisms or integrate across the field-of-view to obtain community- or canopy- or ecosystem-level phenological information.

The Normalized Difference Vegetation Index (NDVI, Tucker, 1979) has been widely used to monitor the timing and magnitude of the seasonal development of the vegetation and link them to environmental factors such as temperature, precipitation and photoperiod (Jolly et al., 2005). The majority of studies focused on satellite data to retrieve phenological signals at regional to global scales (Zhang et al., 2003), or on ground spectral sensors to link NDVI and other vegetation indices to *in situ* biotic and abiotic measurements (Soudani et al., 2014). The coherence in space and time between different NDVI sources (satellite vs near-surface remote sensing) has been explored in boreal and temperate deciduous broad-leaf forests (Liu et al., 2015; Hwang et al., 2014), evergreen forests (Jin and Eklundh, 2014), arid grasslands/savannas (Fensholt et al., 2006). Similarly, satellite vegetation indices have been also compared to camera-based color indices (Klosterman et al., 2014; Hufkens et al., 2012). The cross-scale comparisons between near- and far-remote sensing showed in general better coherence over deciduous than evergreen vegetation (Jin and Eklundh, 2014), and in greenup rather than senescence (Klosterman et al., 2014; Hufkens et al., 2012).

Few studies attempted the in situ comparison between NDVI and camera-based G_{CC} (but see Nasahara and Nagai, 2015). For example, Nagai et al. (2012) examined the relationship between NDVI or the enhanced vegetation index (EVI) and color indices in an evergreen forest in Japan demonstrating the ability of the latter to capture seasonal vegetation cycles. This comparison is often complicated by the different geometry (view angle and field-of-view dimension) of spectral sensors and digital cameras, especially in canopies with complex or multi-layered structures (Ryu et al., 2014; Migliavacca et al., 2011).

Recent developments in camera technology led to inexpensive, near-infrared (NIR) enabled security cameras, allowing the sequential capture of images covering visible-only and of combined visible and NIR images to calculate camera-based NDVI ($NDVI_C$, Petach et al., 2014). Results showed that the seasonal cycle of $NDVI_C$ is almost identical to that of NDVI measured using narrow-band spectral instruments, or retrieved from the moderate resolution imaging spectroradiometer (MODIS), demonstrating the potential of NIR-enabled cameras. The PhenoCam Network (http://phenocam.sr.unh.edu/webcam/) consists now of 340 sites equipped with networked digital cameras, of which two hundred are NIR-enabled cameras such as the ones used in Petach et al. (2014), thereby allowing to extend the analysis across multiple years and different plant functional types.

In the present paper, we analyzed a large dataset of visible plus NIR images across 17 North American sites encompassing six plant functional types (PFT) for a total of 74 year-sites of data from the PhenoCam image archive. Our objectives are:

(a) to compare $NDVI_C$ and G_{CC} seasonal trajectories across different PFT and identify potential differences in their phenology;
(b) to compare $NDVI_C$ and spectral measurements at different scales, including NDVI from MODIS and measured by ground light-emitting diodes (LED) sensors (Ryu et al., 2010);
(c) to examine the consistency between camera-derived phenological transition dates and the MODIS Land Cover Dynamics Product (MCD12Q2) with different methods for deciduous broad-leaf and evergreen needle-leaf forests.

2. Materials and methods

The seventeen sites included in this study belong to the PhenoCam network (http://phenocam.sr.unh.edu/webcam/) and are located in mid-latitude US and Canada (Table 1). The majority of them also belong to other observational networks such as Fluxnet (https://fluxnet.ornl.gov/). Each site is equipped with a NetCam SC IR security camera (StarDot Technologies, Buena Park, CA), featuring a Micron $\frac{1}{2}$" CMOS active-pixel digital imaging sensor and configured for 1.3 megapixel (1296 × 976) output. Camera channels are centered at 600, 530, 450 nm for red, green and blue, respectively (unpublished data). The camera was set at manual (fixed) white balance and automatic exposure. Five sites were also equipped with LED sensors. Peak sensitivities (and full width half maximum, FWHM) of LED sensors were at 646 (56) and 843 (72) nm, for red and NIR, respectively. These self-manufactured spectral sensors were first tested by Ryu et al. (2010) and have proven to be comparable to traditional radiometers.

Extraction of color and vegetation indices. Digital images were processed using the R package `phenopix` (Filippa et al., 2016). For each site one or more region-of-interest (ROI) was chosen, which restricts all subsequent analyses on that subset of pixels. ROIs can be viewed on the PhenoCam web page for each site (http://phenocam.sr.unh.edu/webcam/). RGB images were processed to obtain seasonal trajectories of green chromatic coordinates (G_{CC}, Gillespie et al., 1987). Camera