REQUIREMENTS FOR NEAR-SURFACE REMOTE SENSING DATA ACQUISITION AND PROCESSING AS AN ALTERNATIVE TO TRADITIONAL IN-SITU PHENOLOGY OBSERVATIONS OF CROPS IN BULGARIA

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Abstract: *PhenoCams networks have been operating for more than a decade over vegetated areas to estimate phenology. They apply digital repeat photography that continuously capture images of a given area with an RGB or/and near-infrared enabled cameras. For the first time in Bulgaria, as part of Pheno-Sense project, a PhenoCam will be installed and connected to the PhenoCam cooperative network (https://phenocam.sr.unh.edu/webcam/) that archives and distributes imagery and derived data products from digital cameras deployed at research sites across North America and around the world. The goal of this research is to identify the requirements for near-surface remote sensing data acquisition and processing as an alternative to traditional in-situ phenology observations for crops in Bulgaria*.

ИЗИСКВАНИЯ КЪМ ЗАСНЕМАНЕ И ОБРАБОТКАТА НА БЛИЗКИТЕ ДО ПОВЪРХНОСТТА ИЗОБРАЖЕНИЯ КАТО АЛТЕРНАТИВА НА IN-SITU ФЕНОЛОГИЧНИ НАБЛЮДЕНИЯ НА ЗЕМЕДЕЛСКИ ПОСЕВИ В БЪЛГАРИЯ

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Резюме: *Фенокамери рабоещи в мрежи, повече от десетилетие, наблюдават растителност за оценка на фенологията. Те използват цифрова повторяема фотография, която непрекъснато заснема с камера в RGB и/или близкия инфрачервен диапазон на електромагнитния спектър. За първи път в България, като част от проекта Pheno-Sense съфинансиран по програма COST, ще бъде инсталирана фенокамера и свързана към кооперативната мрежа на PhenoCam (https://phenocam.sr.unh.edu/webcam/), която архивира и разпространява изображения и продукти от данни от цифрови фотоапарати, разположени на изследователски терени в Северна Америка и по света. Целта на това изследване е да идентифицира изискванията за събиране и обработка на данни за дистанционни наблюдения в близост до земната повърхност като алтернатива на традиционните наземни фенологични наблюдения на посеви в България.*

Introduction

Satellite data has been used to estimate phenological indicators in vegetation, such as Start of Season (SoS), End of Season (EoS) and Length of Season (LoS). Traditionally satellite-measured land surface phenology (LSP) is compared to in-situ observations. However, long term field phenological observations, often by volunteers and amateur naturalists, are limited in spatial coverage and ecosystems. The CEOS (Committee on Earth Observation Satellites) LPV (Land Product Validation) subgroup is currently involved in the preparation of a good practice protocol for the use and validation of satellite derived phenological products [1]. The phenology sub-group (https://lpvs.gsfc.nasa.gov/) is working to establish a core set of phenology cameras, PhenoCams, sites.

PhenoCams, digital repeat photography that continuously capture images of a given area with an RGB and near-infrared enabled cameras, networks have been operating for more than a decade over vegetated areas to monitor phenology. The phenological research community have adopted near-surface remote sensing as an alternative to traditional in-situ observations for different natural ecosystems with regard to carbon cycles (e.g., productivity, CO2 flux) [2], [3], management of natural resources in arid ecosystems [4], forest phenology [5–9] rangelands [10]. Some of the studies report relatively good agreement between the satellite-retrieved and PhenoCam-retrieved phenological indicators, others find no correlation between the two data sources. The non-alignment between the two data sources are linked to the differences in the scale of observation, some of the PhenoCams do not acquire images in the NIR wavelengths [10], the choice of the VI used to monitor phenological indicators or the representation of the site by the ROI [11]. However, different PhenoCam (StarDot NetCam SC) sensors had similar response functions, regardless of sensor age and previous deployment conditions [12]. This finding support our hypothesis that, even if very few studies have considered monitoring phenological indicators with PhenoCams for cropland areas [13–15], we could develop a methodology that uses PhenoCam data as proxy for traditional in-situ phenological observations.

The goal of our research is to assess the near-surface remote sensing data and its alternative to traditional in-situ observations for time-series analysis of satellite-measured land surface phenological indicators for crops. For this purpose, for the first time in Bulgaria, a PhenoCam will be installed and connected to the PhenoCam cooperative network (https://phenocam.sr.unh.edu/webcam/) that archives and distributes imagery and derived data products from digital cameras deployed at research sites across North America and around the world. The PhenoCam will monitor crop fields in Bulgaria.

In this study, we examined the literature to answer the following questions:

- What are the requirements for the near-surface remote sensing data acquisition for crop canopy in Bulgaria?
- What are the requirements for the near-surface remote sensing data processing for crop phenology estimation?
- How strong is the agreement between the near-surface remote sensing and satellite derived phenological events?

Comparison of Satellite and PhenoCam data

PhenoCam data is often used in studies to compare satellite and PhenoCam measurement. Richardson [16] has made one of the recent reviews on PhenoCam network and its specific applications varying from close-up observation of individual organisms; long-term canopy-level monitoring at individual sites; automated phenological monitoring in regional-to-continental scale observatory networks; and tracking responses to experimental treatments to name but a few. A year later, a team led by Seyednasrollah et al. [17] but from the same team of Richardson covers the newly released PhenoCam 2.0 data for vegetation phenology studies.

One of it utilizes the Geostationary Operational Environmental Satellites (GOES-16 and GOES-17) data which can monitor NDVI at temporal scales comparable to that of PhenoCam. The study is applicable for the western hemisphere as GOES satellites "hang over" it. The Wheeler and Dietze [18] study the phenology of deciduous broadleaf forests for the first 2 full calendar years of data (2018 and 2019) by fitting double-logistic Bayesian models and comparing the transition dates of the start, middle, and end of the season to those obtained from PhenoCam and MODIS 16 d NDVI and enhanced vegetation index (EVI) products. Compared to these MODIS products, GOES has a better correlation with PhenoCam at the start and middle of spring but had a larger bias at the end of spring. Similarly,

Thapa et al. [19], utilize a time series of Normalized Difference Vegetation Index (NDVI), Green Chromatic Coordinate (GCC), and Normalized Difference of Green & Red (VIgreen) indices from MODIS, Sentinel-2 to assess Forest Phenology. Phenophase transition dates were estimated and validated against visual inspection of the PhenoCam data and the Start of Spring and End of Spring could be predicted with an accuracy of <3 days with GCC, while these metrics from VIgreen and NDVI resulted in a slightly higher bias of (3–10) days. The observed agreement between UAV_{NDVI} vs. satellite NDVI and PhenoCamGCC vs. satellite GCC suggested it is feasible to use PhenoCams and UAVs for satellite data validation and upscaling. For the deciduous forest phenology PhenoCam was benchmarked against the use of MODIS and Advanced Very High Resolution Radiometer (AVHRR) satellite data by the team of Klosterman et al. [20]. The authors emphasize that dates derived from analysis of high-frequency PhenoCam imagery have smaller uncertainties than satellite remote sensing metrics of phenology. They continue also that dates derived from the remotely sensed enhanced vegetation index (EVI) have smaller uncertainty than those derived from the normalized difference vegetation index (NDVI).

Wang et al. [21] in their proof of concept multi-scale observations of dry-season green-up in an Amazon tropical evergreen forest use a cross-calibrated PlanetScope data using BRDF-adjusted MODIS data on a set of 22 dates in 2018 and 16 in 2019, all from the six drier months of the year. They point out that the PlanetScope data accurately assessed seasonal changes in ecosystem-scale and crown-scale spectral reflectance; are consistent with local PhenoCam observations with R2 around 0.8.

An interesting find is the study of Norris and Walker [22], who found that PhenoCam data confirm warm-season peaks in a pinyon-juniper system in Arizona, USA. However, notably solar-sensor geometry explains >80% of variability in pinyon-juniper satellite NDVI and shadowing is the likely cause of false winter increases in NDVI. This makes NDVI an inappropriate phenological tool across widespread western ecosystems. Probably this can be confirmed also for the Eastern hemisphere.

Bornez at al. [23] assess the VEGETATION and PROBA-V Phenology Using PhenoCam and Eddy Covariance Data. They validated the LSP estimates with near-surface PhenoCam and eddy covariance FLUXNET data over 80 sites of deciduous forests. Their results showed a strong correlation (R2 > 0.7) between the satellite LSP and ground-based observations from both PhenoCam and FLUXNET for the timing of the SoS and R2 > 0.5 for the EoS. Liu and Wu [24] have used a combination of large regional satellite indices from MODIS, 676 site-year local data (FLUXDATA) covering seven vegetation types, and 57 site-year regional data (PhenoCam) to get insight for the temporal and spatial variability of net ecosystem productivity (NEP) which is considered critical for coupling ecosystem carbon (C) cycle and climate system. Yan et al. [25] compared vegetation greenness indices from PhenoCam and satellite (Landsat and MODIS) observations against GPP estimates from the eddy covariance technique, across three representative ecosystem types – mainly drylands - of the southwestern USA. Their study is focused more on the VI-GPP relationships which concluded that the VI well captures the changes in GPP in a longer run, whereas other ways of tracking of GPP changes should be found in a shorter term.

For Australian ecosystems the team led by Moore et al. [26], make a comprehensive review of the joint use of satellite and PhenoCam data. In effect, the authors claim that overall, PhenoCams are useful for understanding ecosystem-scale Australian vegetation phenology. Watson et al. [27] studied temperate grasslands phenology through multi-scale approach involving PhenoCam. They used MODIS/Landsat satellite products to assess paddock-to-landscape functioning of twelve grassland areas dominated by cool season and warm season, native or exotic grasses near Canberra, Australia. However, similarly to other teams they conclude that, the higher temporal fidelity of the cameras captured changes in vegetation not observed in the coarser satellite or field results. The PhenoCam data shows consistent periods of increasing and decreasing greenness over as little as 5 days which is typically not the case of satellite observations.

For North America grasslands this is done by the team of Cui et al. [28]. In this study, they used PhenoCam green chromatic coordinate (GCC) to evaluate grassland phenology derived from three types of MODIS vegetation indices: NDVI, enhanced vegetation index (EVI), and a per-pixel GCC (GCCpp) which was computed to describe the average vegetation color at the pixel level. Similarly to other teams, they conclude that GCCpp can be more suitable than NDVI and EVI at estimating dynamics in grassland greenness during senescence.

In Europe, Luo et al. [29] evaluated the consistency between structural (VIs) and physiological (GPP) phenology for tree-grass ecosystem at four Mediterranean sites. Where the VIs are computed from PhenoCam data and GPP is derived from eddy covariance flux tower measurement. They suggest using multiple VIs to better represent the variation of GPP.

PhenoCam Data acquisition

To minimize shadowing and bidirectional reflectance distribution function (BRDF) effects caused by variations in illumination geometry, some studies [30], [31] recommend to acquire near-noon images. However other studies [9] argue that acquiring data during all daytime further minimize the influence of changes in scene illumination. Very interesting approach is described by Sakamoto et al. [14], where images are acquired during daytime and nighttime. The nighttime images are for calibrating the DN for the camera derived VI calculation.

Because the FOV of the digital camera often contained non-canopy features, manually defined regions of interest (ROIs) incorporating only the vegetation canopy is usually analyzed. Brown et al. [30] restricted the ROIs to the foreground of the image to minimize the effects of atmospheric aerosols and low-lying cloud. Petach et al. [32] draw attention to the mismatch between the camera field of view and the satellite pixel when comparison between the two sensor is studied. He also concludes that high-quality data on the seasonal variation in canopy NDVI is possible to obtain without reference panel for calibration of the PhenoCam images. This is confirmed by the experience from Richardson A. (personal communication), when the camera is configured with fixed white balance. Brown et al. [33] emphasize the importance to maintain the same camera FOV during the whole measuring period.

PhenoCam Data processing

Near-surface remote sensing data are subject to minimal atmospheric effects because of the short atmospheric path associated with them. Nevertheless, noise may be introduced by external conditions and variations in scene illumination. To suppress such noise several statistical approaches are described in the literature. One approach [31, 34] uses the original images, by averaging into a single daily scene the collected data each day. These daily averages then are filtered using a mean kernel to reduce data volumes and the effects of plants moving and a VI is calculated. Another approach is to first calculate the VI and then apply either averaging or 90th percentile of all daytime values [9]. Different spectral indices, Table 1, exists to extract indicative for the vegetation activity.

Table 1. List of vegetation indices effective in detecting vegetation phenophases from PhenoCam and satellite data. Where Nir, Green, Red and Blue are mean digital number (DN) values in the bands of the PhenoCam image or the spectral reflectance values for the satellite bands

Vegetation index	Reference PhenoCam	Studied Satellite	Reference Satellite
$\mathrm{GCC} = \frac{\mathrm{Green}}{\mathrm{Red} + \mathrm{Green} + \mathrm{Blue}}$	[2], [9], [12], [15], [19], [20], [24], [30]	Sentinel-2	[2], [19]
$\mathrm{ExG} = 2 * \mathrm{Green} - \mathrm{Red} - \mathrm{Blue}$	[9], [14], [31]		
$\mathrm{VARI\_1} = \frac{\mathrm{Green} - \mathrm{Red}}{\mathrm{Green} + \mathrm{Red} - \mathrm{Blue}}$	[35]		
$\mathrm{VARI\_2} = \frac{\mathrm{Green} - \mathrm{Red}}{\mathrm{Green} + \mathrm{Red}}$	[14]	MODIS	[14]
$\mathrm{VIgreen} = \frac{\mathrm{Green} - \mathrm{Red}}{\mathrm{Green} + \mathrm{Red}}$	[19], [36]	Sentinel-2	[19]
		MODIS	[19]
$\mathrm{NDVI} = \frac{\mathrm{Nir} - \mathrm{Red}}{\mathrm{Nir} + \mathrm{Red}}$	[14], [18], [22]	Sentinel-2	[2][19]
		MERIS	[30]
		MODIS	[14], [18]–[20], [22], [24]
		GEOS	[18]
$\mathrm{CIgreen} = \frac{\mathrm{Nir}}{\mathrm{Green}}$	[14]	MODIS	[14]
$\mathrm{MGCC} = \frac{\mathrm{Green}}{\mathrm{Blue} + \mathrm{Green} + \mathrm{Nir}}$		MERIS	[30]
$\mathrm{EVI} = G * \frac{\mathrm{Nir} - \mathrm{Red}}{\mathrm{Nir} + C1 * \mathrm{Red} - C2 * \mathrm{Blue} + L}$ with G = 2.5, C1 = 6, C2 = 7.5 and L = 1	[18]	Landsat TM	[31]
		Landsat ETM+	[15], [31]
		MODIS	[18], [20], [24]
		EPIC	[15]
$\mathrm{OSAVI} = Y * \frac{\mathrm{Nir} - \mathrm{Red}}{\mathrm{Nir} + \mathrm{Red} + Y}$ with Y = 0.16		MODIS	[24]
$\mathrm{SR} = \frac{\mathrm{Nir}}{\mathrm{Red}}$		MODIS	[14]

Richardson et al. [12] recommend to use the changes in the position of the horizon line of each image to diagnose camera field of view shifts and to account for each shift before further processing the data.

Many PhenoCam data processing tools, in MATLAB, Python and R, are listed in the "Image Analysis Tools" section by PhenoCam project page (https://phenocam.sr.unh.edu/webcam/tools/) or from the corresponding author [37].

In camera-based phenology detection, the half-max is commonly used to detect the dates of start and end of season [34].

Conclusions

The agreement between the near-surface remote sensing and satellite derived phenological indicators is still on-going research area. When scaling from camera plot to landscape plot, the agreement between satellite and camera derived estimates of key phenological events was stronger for green-up than for senescence [2], [31]. Satellite-driven phenology tends to predict an earlier start of growing season and later end of growing season than camera-driven [36]. Homogeneous vegetation sites have higher correlation between the satellite derived and camera derived phenology [36] than the mixed canopy sites.

The requirements for the near-surface remote sensing data acquisition for crop canopy in Bulgaria are:

- The images will be acquired between every hour day and night
- ROI will best represent the studied crop field
- No reference panel will be installed
- The camera will not be moved during the whole crop growing season
- The camera will be configured according to all "Camera Setup and Installation" section by PhenoCam project page (https://phenocam.sr.unh.edu/webcam/tools/)

In addition to the PhenoCam data, in-situ phenological data will be recorded following the protocol defined by Denny et al. [38].

The requirements for the near-surface remote sensing data processing for crop phenology estimation:

- All VI from Table 1 will be tested
- For each channel, the mean and standard deviation, as well as the 5th,10th, 25th, 50th (median), 75th, 90th, and 95th percentile values, of the DN distribution across all pixels in the ROI will be determined [12]
- For each channel a 3-day moving window will be tested
- The phenological indicators will be computed with DATimeS [39]

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