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POLISH PHENOLOGICAL CAMERA NETWORK, NATUREVIDO: IMPLEMENTATION, CAPABILITIES, PRELIMINARY RESULTS

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Abstract. In a changing climate, phenological observations are a key tool in assessing climate change impact on vegetation. Phenocameras are increasingly being used worldwide as a new tool in phenological research. The Polish Naturevido phenocamera network, established in 2020, uses them to monitor various ecosystems, enabling analysis of both the whole vegetation cover and individual plants. To demonstrate the network's capabilities, regions of interest (ROIs) representing woody species and herbaceous species separately were designated for images from 2024. Average colour parameters within each ROI have been calculated. Based on the phenophase extraction, start of season (SOS) was determined to range from day of the year (DOY) 79 to 119 and from DOY 64 to 113, for woody and herbaceous plants, respectively. End of season (EOS) ranged from DOY 282 to 314 for woody plants, and from DOY 200 to 40 (of following year) for herbaceous plants. EOS was determined within a wider uncertainty range than SOS. The most pronounced season-length difference was between peatland and urban sites.

Key words: digital repeat photography, end of season, greenness, growing season, phenology, phenocamera, phenological network, start of season

Introduction

In recent years, there has been growing interest in phenological research, which describes seasonal changes in plant development and their responses to both biotic and abiotic factors, such as pest outbreaks or temperature (Lieth 1974). Due to the changing climate, the European region is warming, and the temperature rise is faster than the global average. The year 2024 was reported as the warmest year on record for the continent (Copernicus Climate Change Service (C3S, 2025). Understanding the potential threats and consequences of climate change for vegetation is becoming an urgent priority, as we are already observing shifts in plants' growing seasons (Bellini *et al.* 2022; Szwed *et al.* 2025; Willems *et al.* 2022) and species distributions (Bradley *et al.* 2009; Dyderski *et al.* 2018) driven by the climate crisis.

Phenological observations are to this day conducted directly in the field, using designated locations and observers and several selected plant species. Poland, as other European countries, has an observation network based on guidelines for conducting observations (Koch *et al.* 2007; Szwed *et al.* 2025). However, new technological achievements have expanded the scale of phenological research, initially to a global scale using satellites and, in recent years, to near-surface observations utilising monitoring cameras called phenocameras

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(Richardson 2019). This latter approach to phenological research is rapidly developing, as RGB cameras are inexpensive and widely available, making them an easy-to-implement addition to other instruments used in environmental monitoring. As they are not restricted to the exact species observed, unlike conventional observations, they are a suitable tool for vegetation productivity, carbon balance and water balance analyses, and thus complement sites conducting such measurements. Currently, the largest worldwide network is PhenoCam, an ecosystem phenology camera network established by Northern Arizona University (Richardson *et al.* 2018; Richardson 2023). Although many cameras are located in Europe, Poland is not covered by the network. To fill this gap, in 2020, work began on creating a Polish observation network using phenocameras, thanks to the efforts of Poznań University of Life Sciences (PULS). Since the installation of the first camera in 2020, the PULS network called Naturevido has been continuously collecting vegetation images for various ecosystems in Poland.

The aim of this article is to present the PULS phenocamera network: the sites included and their vegetation types; the modules used to capture images; the initial phenological results from the sites; comparisons with other methods of plant observations; and the challenges encountered in establishing and maintaining the network.

Sites and methods

Sites

The Naturevido network was established in 2020 by scientists from the Department of Bioclimatology (DB) at the Poznań University of Life Sciences (PULS). The first camera was installed at the PULS peatland station at Rzecin (Fig. 1), serving as a complementary sensor to the eddy covariance equipment. Subsequent cameras installed shortly thereafter and in the following years, however, were intended solely for phenological purposes. The network aims to cover various locations representing the eight natural-forest provinces (Tab. 1), characterised by distinct climatic conditions (Zielony, Kliczkowska 2012). Therefore, the network covers observations primarily in mixed and deciduous forests (Zielonczyn, Janików, Rowokół, Krusznik, Ustrzyki Górne, Wołosate). At the time of writing this article, cameras are absent in the provinces IV, VI and VII (Masovia-Podlachia, Lesser Poland and Sudeten Mountains, respectively). Cameras in botanical gardens and arboreta (Poznań – PULS Dendrological Garden, Zielonka, Kórnik), on the other hand, provide an opportunity to compare phenocamera monitoring against conventional observations, which are often conducted in such institutions. Other vegetation types monito-

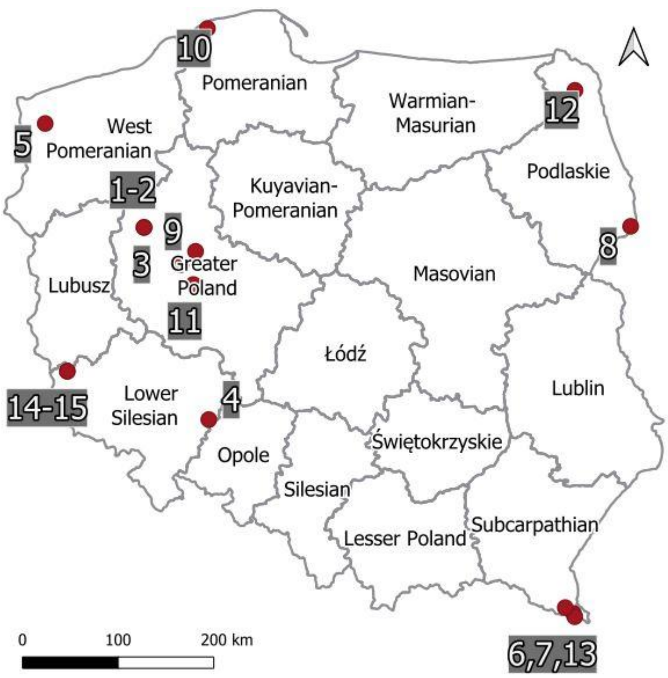


Fig. 1. Naturevido phenocamera network sites across Polish voivodeships
The ID numbers correspond to the order in which the cameras were installed: 1-2 – Rzecin, 3 – Poznań, 4 – Janików, 5 – Zielonczyn, 6 – Wołosate, 7 – Ustrzyki Górne, 8 – Białowieża, 9 – Zielonka, 10 – Rowokół, 11 – Kórnik, 12 – Krusznik, 13 – Wetlina, 14-15 – Ruszów

Table 1

Basic information about the Naturevido network
Natural-forest provinces codes are: I – Baltic Coast, II – Masuria-Podlachia, III – Greater Poland-Pomerania, V – Silesia, VIII – Carpathian Mountains.
CORINE Land Cover IDs are: 1.4.1 – green urban areas, 1.4.2 – sport and leisure facilities, 2.3.1 – pastures, 2.4.2 – complex cultivation patterns, 2.4.3 – land principally occupied by agriculture, with significant areas of natural vegetation, 3.1.1 – broad-leaved forest, 3.1.3 – mixed forest, 4.1.1 – inland marshes

No.	site ID	Natural--forest province ID	CORINE Land Cover ID	Installation date	Additional measurements
1	Rzecin (tower)	III	4.1.1	19.07.2020	Eddy covariance
2	Rzecin (cabins)	III	2.3.1	28.10.2020	
3	Poznań	III	1.4.2	30.11.2020	Conventional phenological observations
4	Janików	V	3.1.1	23.04.2021	
5	Zielonczyn	I	3.1.3	30.04.2021	
6	Wołosate	VIII	2.3.1, 3.1.3, 3.1.1	17.05.2021	
7	Ustrzyki Górne	VIII	2.4.2, 3.1.3, 3.1.1	21.05.2021	
8	Białowieża	II	1.4.1	24.05.2021	
9	Zielonka	III	2.4.3	14.02.2022	
10	Rowokół	I	3.1.3	05.07.2022	
11	Kórnik	III	3.1.3	06.02.2024	Conventional phenological observations
12	Krusznik tower	II	2.3.1, 4.1.1, 3.1.1	18.03.2024	
13	Wetlina	VIII	3.2.1, 3.1.1	01.05.2024	
14	Ruszów 1	V	2.3.1	20.06.2024	
15	Ruszów 2	V	2.3.1	20.06.2024	

red within the network include parks (Białowieża), sites with invasive species (Ruszów 1 and 2), semi-natural grasslands such as pastures and meadows (Wołosate, Wetlina), ruderal plant communities (Rzecin cabins) and even lawns that are regularly mowed and watered (Kórnik). For some cameras, it is possible to analyse several types of vegetation within a single Field of View (FoV). Overall, the network comprises 15 cameras across 13 sites. Table 1 presents details for each site, including the natural-forest province ID, CORINE Land Cover ID (CLC2018), installation date and additional data collected from the site if present.

To compare vegetation status between sites for this article, imagery data from 2024 were selected, as this year provides the most complete Naturevido dataset. However, data from three sites (Janików and Ruszów 1 and 2) are missing for this time period due to midseason installation (Ruszów) or malfunction causing data unavailability for the entire year (Janików).

Camera module

Naturevido is based on Dahua monitoring cameras (Zhejiang Dahua Technology Co., Ltd, China); therefore, the network does not follow the protocol of The PhenoCam Network (Richardson 2023), which is the worldwide phenocamera system using StarDot technology (StarDot Technologies, California). Following the conclusions of Sonnentag *et al.* (2012) regarding the incorporation of monitoring cameras from various manufacturers into phenological research, we opted for a readily available, cost-effective alternative in our area. Unknown camera models used in this network are those installed by third parties, such as national parks (Wołosate, Ustrzyki Górne, Krusznik, Wetlina), utilising recordings on their websites to promote the aesthetic values of the parks.

For phenocameras installed by DB (PULS), the standard module includes: a Dahua camera, an SD card as backup storage, a GSM router for transmission, a handle and a protection box

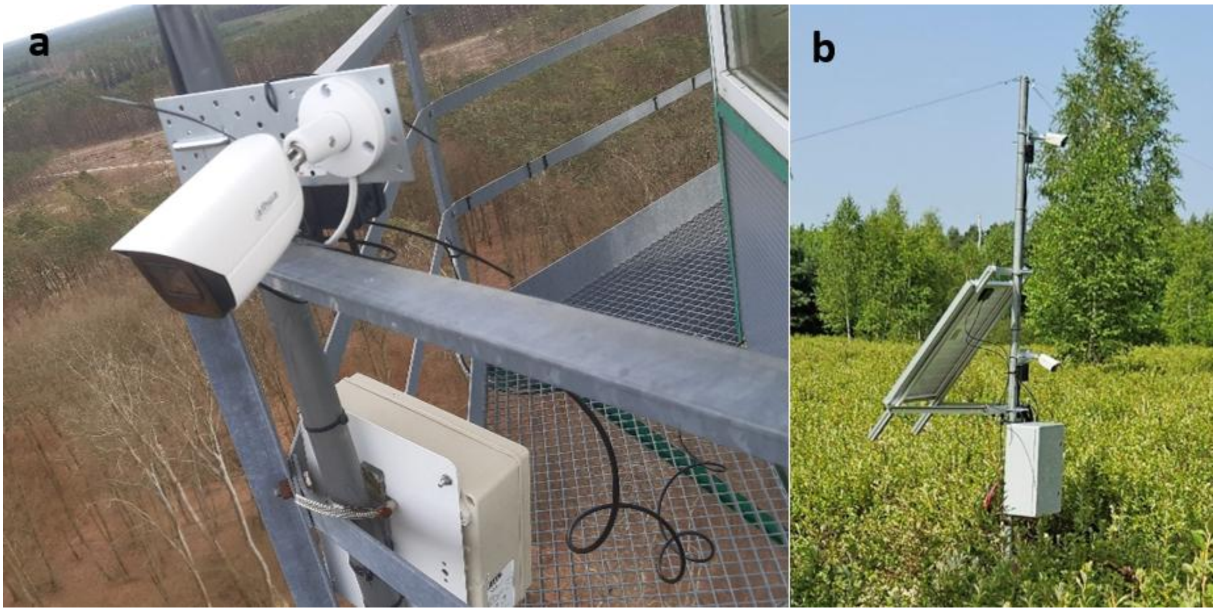


Fig. 2. Basic camera module designed for sites with electric grid power available (a) and unavailable (b)

(Fig. 2a). Access to electric power is preferable; thus, cameras are installed on buildings or fire/observation towers. If the camera has a direct local internet connection with the building owner's agreement, the router and protection box can be bypassed. The standard module must be expanded if there is no access to mains electricity on site. Additional components include a solar panel, a battery, an automatic controller switchbox and a solar regulator (Fig. 2b).

The basic method for collecting images involves real-time transmission from the camera to the university server. SD cards are the backup option reserved for when the server is unavailable or undergoing maintenance. Only third-party cameras do not provide continuous image recording in the event of any transmission malfunction. Cameras record vegetation at various time intervals, ranging from 1 to 15 minutes. Images are collected continuously, resulting in thousands of images per year. The camera's position is fixed; however, the FoV changed in some sites due to unintended camera movement or the replacement of a failed camera.

Image processing

Collected image time series are processed with the *phenopix* package (Filippa *et al.* 2016), written in the R programming language (R core team 2025) specifically for phenocamera image analysis. To extract the optical properties from the images, the region of interest (ROI) is selected (Tab. 3). Each colour parameter is calculated from the averaged ROI pixels' digital numbers, and the standard deviation is additionally calculated for each averaged value, representing one image. Table 2 presents all colour parameters estimated using the *phenopix* package, along with the formulas and theoretical ranges for every vegetation index. However, in practice, when recording vegetation cover, G_i ranges from approximately 0.3 to 0.5, and other indices are also far from their extremes.

The colour value for each image is aggregated into daily chromatic coordinates (R_{CC}, G_{CC} and B_{CC}), which are the medians of the RGB indices. Using the max filter provided by the package, the 90^{th} percentile G_{CC} value in a three-day moving window is also extracted for every day of phenocamera observations (Sonnentag *et al.* 2012). Finally, G_{CC} values are used to determine seasonal plants' growth and the start/end of season (SOS and EOS) using five approaches to fitting a greenness curve and four methods of phenophase extraction (Gu *et al.* 2009; Klosterman *et al.* 2014; Filippa 2020).

Results

Seasonal colour dynamics

An example of seasonal variation in vegetation's optical characteristics is shown in Fig. 3, which presents the ROI from the herbaceous section of the Zielonka arboretum site. G_{CC} enables tracking

Table 2

Vegetation indices based on RGB values calculated with the *phenopix* package (Filippa *et al.* 2016)

Abbreviation	Full name	Formula	Theoretical range
R_{dn}	red digital number	$R_{dn} = \frac{1}{n}\sum_{i=1}^{n}(R_1 + \ldots + R_n)$	0–255
G_{dn}	green digital number	$G_{dn} = \frac{1}{n}\sum_{i=1}^{n}(G_1 + \ldots + G_n)$	0–255
B_{dn}	blue digital number	$B_{dn} = \frac{1}{n}\sum_{i=1}^{n}(B_1 + \ldots + B_n)$	0–255
G_i	green index	$G_i = \frac{G_{dn}}{R_{dn} + G_{dn} + B_{dn}}$	0–1
R_i	red index	$R_i = \frac{R_{dn}}{R_{dn} + G_{dn} + B_{dn}}$	0–1
B_i	blue index	$B_i = \frac{B_{dn}}{R_{dn} + G_{dn} + B_{dn}}$	0–1
BRI	Brightness	$BRI = R_{dn} + G_{dn} + B_{dn}$	0–765
GEI	green excess index	$GEI = 2G_{dn} - (R_{dn} + B_{dn})$	-510–510

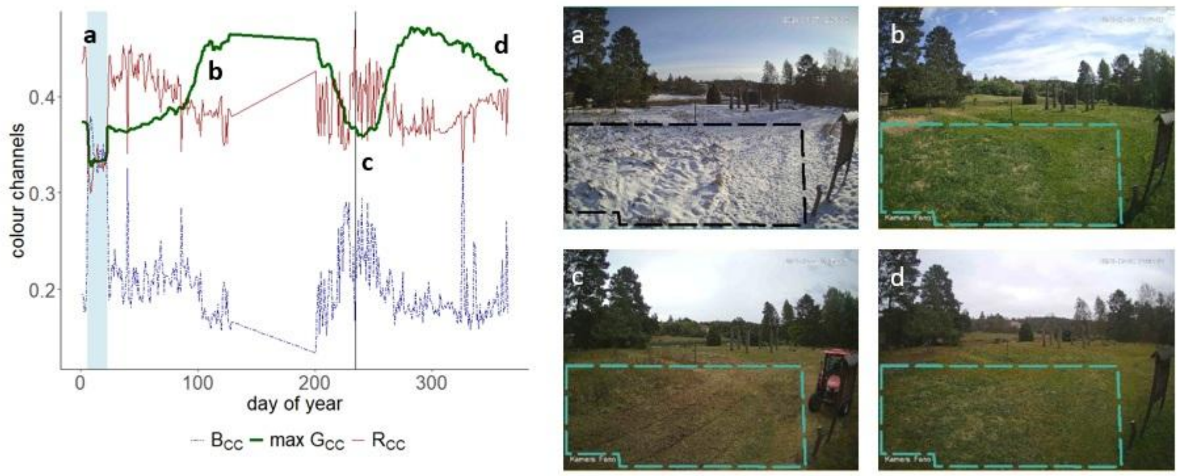
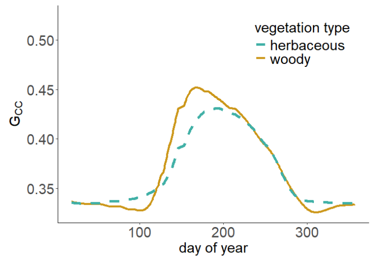
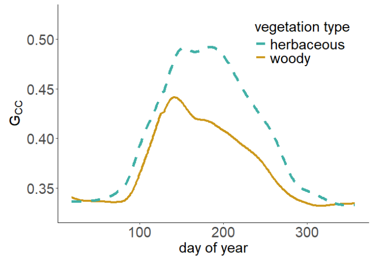
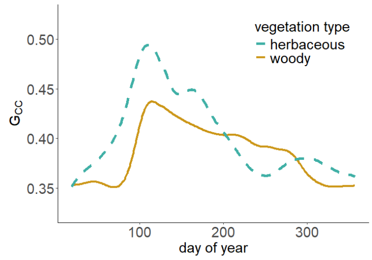
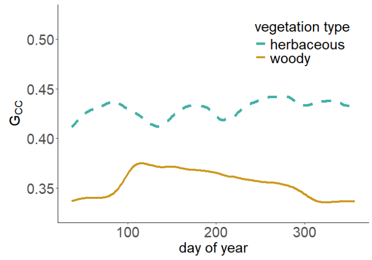
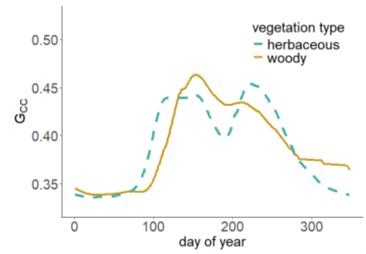
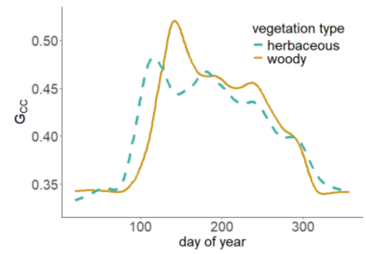


Fig. 3. Red (red dashed line), green (green solid line) and blue (blue dotted line) chromatic coordinates representing seasonal optical changes in the lawn at the arboretum in Zielonka in 2024 (left). The light-blue rectangle represents the period with snow cover, and the black vertical line represents the mowing event in late summer. For the period May–July, images were not collected
Images on the right are from dates: a – February 7th, b – May 8th, c – August 22nd, d – December 30th

seasonal plant growth: it reaches higher values than R_{CC} around the time the season starts, then peaks (b). Dead parts of perennials caused R_{CC} to increase above G_{CC} again in summer, and, after mowing, G_{CC} rose to a level similar to that of the first peak of the year. The snowless December of 2024 (d) enabled continuous recording of vegetation status, which, despite the year coming to an end, had not yet reached the baseline G_{CC} value. However, at the beginning of 2024, the blue channel (B_{CC}) indicated the presence of snow (a). With snow cover, the RGB chromatic coordinates

Table 3

Regions of interest (ROIs) across six sites with both woody (yellow solid line) and herbaceous (turquoise dashed line) plants in the camera FoV with corresponding greenness curves for year 2024

Site	Regions of interest	Greenness curves
Rzecin (tower)		
Rzecin (cabins)		
Poznań		
Kórnik		
Wołosate		
Białowieża		

tend to equalise (to ~0.33), indicating a similar contribution of the three channels in the ROI – that is, blackish or whiteish colour depending on the brightness of the pixels in the ROI. While snow is present on the site, pixel brightness is at its highest levels of the year. B_{CC} can even predominate over other colours during long periods of substantial snow cover.

Start and end of phenological season

We found that the season onset and its end are more straightforwardly determined for ROIs covering image fragments with woody plants (mainly deciduous trees across all sites) than for ROIs covering some areas with herbaceous plants (Tab. 3, especially at the Kórnik site). For this reason, we divided the results into two sets: woody (Tab. 4) and herbaceous plants (Tab. 5). Depending on the curve-fitting and phenophase-extraction methods, the beginning (SOS) and end of the season (EOS) may fall on different dates. We chose spline greenness curve fitting because it provides the most accurate representation of seasonal changes in the G_{CC}.

In methods based on thresholds and derivatives, the start of the season is designated based on a 50% threshold of the increasing/ decreasing trajectory of G_{CC} (Filippa 2020), whereas phenophase extraction functions proposed by Klosterman *et al.* (2014) and Gu *et al.* (2009) recognise the SOS earlier at the increasing trajectory of seasonal G_{CC} rise and, similarly, EOS later at the decreasing trajectory. The latter method is more consistent with conventional observations of leaf development at sites with additional phenological data (Poznań and Kórnik); therefore, it was chosen for further analysis (Fig. 4a).

Fitting can also be combined to obtain uncertainty estimation (here we present the 25th––75th percentile range, Fig. 4b). Visual inspection of the fitting results indicated that the latter two methods (Klosterman and Gu used together in combined fitting) yielded the fewest errors when used to designate SOS and EOS in this research.

For ROIs containing woody plants, both methods yielded the same order of season onset across sites; however, the exact dates differed by 1–6 days. The earliest start of the phenological season occurred in locations close to each other and serving a similar function – namely, arboreta in Zielonka, Kórnik and Poznań. On the other hand, the SOS was latest (by 32–40 days depending on method) at the Rzecin (tower) site, located in the middle of a peatland.

The determination of end of season for ROIs with woody plants is somewhat inconsistent between the two methods. The EOS dates differed by 0–12 days between methods (excluding two sites: Krusznik, whose registering of an extremely short season is probably due to improper camera settings resulting in few high G_{CC} peaks from oversaturated images; and Wołosate, where, by EOS, the camera FoV had changed). The Rzecin tower site has the earliest season offset, and Białowieża marks the end of the phenological season at the latest. The difference between those two sites is 28–33 days, depending on method.

A comparison of the normalised greenness curves between the most distant locations in Poland in north–south and east–west directions, and between the urban site (Poznań) and non-urban sites, shows the variability in phenological season length (Fig. 5). In eastern and western Poland, SOS and EOS dates are almost identical, differing by 1–2 days (7–9 days for SOS/EOS uncertainty estimation). Figure 4 confirms that SOS is very similar for those sites. For northern and southern Poland, the Rowokół and Wołosate, SOS differs by 6–14 days, with the SOS being earlier at Wołosate. Due to the FoV change at Wołosate during senescence, the EOS difference between sites, which reaches even 47 days, may be an incorrect estimate. A comparison of the urban site (Poznań, one of Poland's largest cities) and the Rzecin cameras, located far from any city (the Rzecin tower is also far from any buildings) reveals the largest differences in growing-season patterns. Here, Poznań starts season 31–36 days earlier than the peatland site; however, the Rzecin cabins site's SOS is only 3–6 days later than Poznań's. Rzecin's season is also shorter; EOS is 4–16 days earlier at the tower site and 12–28 days earlier at the cabins.

SOS phenophase extraction is much more inconsistent across methods for herbaceous than woody plant ROIs. Moreover, in some cases, extracted phases indicate an extremely short phenological season, or SOS extraction failed, marking the second half of the year as the onset of seasonal growth (Tab. 5). Nevertheless, the comparison of the earliest and latest SOS dates among the herbaceous plants indicates a 49-day difference (by the combined fitting method) between Poznań and Rzecin tower sites. EOS variability between sites ranges from 113 to 139 days.

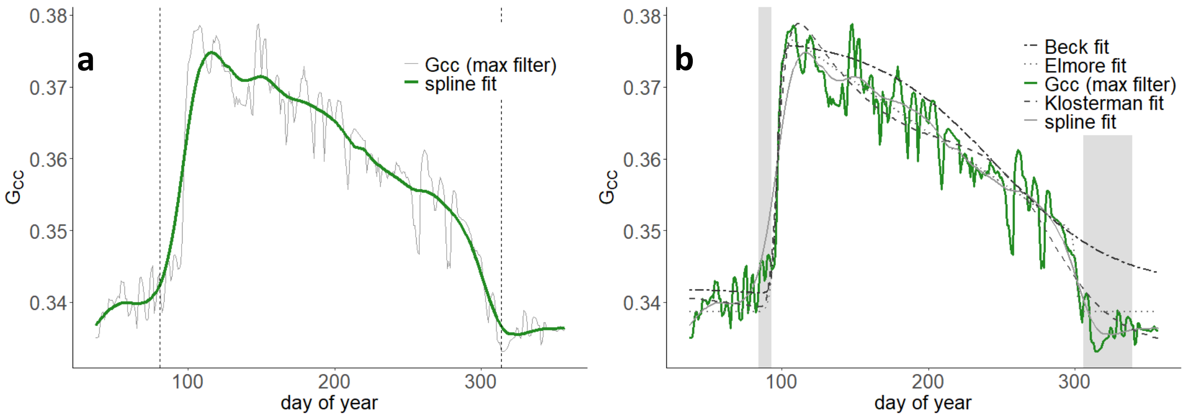


Fig. 4. Greenness curve fitting and two methods of phenophase extraction for the Kórnik site
a – spline fitting (green thick line) with max filtered G_{CC} values (thin grey line), dashed vertical lines indicate SOS and EOS (from left to right) designated by Gu method
b – max filtered G_{CC} (green thick line), combined fitting method (grey to black thin lines), SOS and EOS with uncertainty estimation (25^{th}–75^{th} percentiles) by Klosterman+Gu method indicated with grey rectangles

Table 4

Start of season (SOS) and end of season (EOS) in 2024, day of year (DOY) and date for each ROI referring to woody plants, for spline-fit greenness curves with the Gu phenophase extraction method and combined fit with Gu+Klosterman phenophase extraction

Site	Spline fit, Gu phenophase extraction				Combined fit, Klosterman+Gu phenophase extraction							
	SOS		EOS		SOS				EOS			
					25%		75%		25%		75%	
	DOY	date	DOY	date	DOY	date	DOY	date	DOY	date	DOY	date
Zielonka	79	19-03	309	4-11	83	23-03	89	29-03	297	23-10	318	13-11
Kórnik	81	21-03	314	9-11	84	24-03	93	2-04	306	1-11	339	4-12
Poznań	83	23-03	310	5-11	84	24-03	92	1-04	298	24-10	354	19-12
Rzecin (cabins)	89	29-03	282	8-10	87	27-03	92	1-04	286	12-10	296	22-10
Ustrzyki Górne	99	8-04	295	21-10	98	7-04	110	19-04	300	26-10	311	6-11
Wołosate	102	11-04	307	2-11	98	7-04	111	20-04	347	12-12	361	26-12
Białowieża	104	13-04	315	10-11	98	7-04	108	17-04	314	9-11	353	18-12
Krusznik	106	15-04	174	22-06	105	14-04	116	25-04	244	31-08	341	6-12
Zielonczyn	106	15-04	314	9-11	107	16-04	115	24-04	307	2-11	320	15-11
Rowokół	108	17-04	303	29-10	112	21-04	118	27-04	300	26-10	309	4-11
Rzecin (tower)	119	28-04	294	20-10	115	24-04	121	30-04	294	20-10	300	26-10

Table 5

Start of season (SOS) and end of season (EOD) in 2024, day of year (DOY) and date for each ROI referring to herbaceous plants, for spline-fit greenness curves with the Gu phenophase extraction method and combined fit with Gu+Klosterman phenophase extraction

Site	Spline fit, Gu phenophase extraction				Combined fit, Klosterman+Gu phenophase extraction							
	SOS		EOS		SOS				EOS			
					25%		75%		25%		75%	
	DOY	date	DOY	date	DOY	date	DOY	date	DOY	date	DOY	date
Poznań	60	29-02	179	27-06	64	4-03	72	12-03	219	6-08	237	24-08
Rzecin cabins	88	28-03	293	19-10	72	12-03	81	21-03	296	22-10	304	30-10
Zielonka	244	31-08	238	25-08	76	16-03	213	31-07	261	17-09	409	12-02*
Białowieża	80	20-03	184	2-07	81	21-03	86	26-03	339	4-12	356	21-12
Wołosate	81	21-03	293	19-10	81	21-03	88	28-03	301	27-10	314	9-11
Wetlina	106	15-04	204	22-07	110	19-04	122	1-05	200	18-07	208	26-07
Rzecin tower	125	4-05	286	12-10	113	22-04	120	29-04	286	12-10	292	18-10

* Next year (2025)

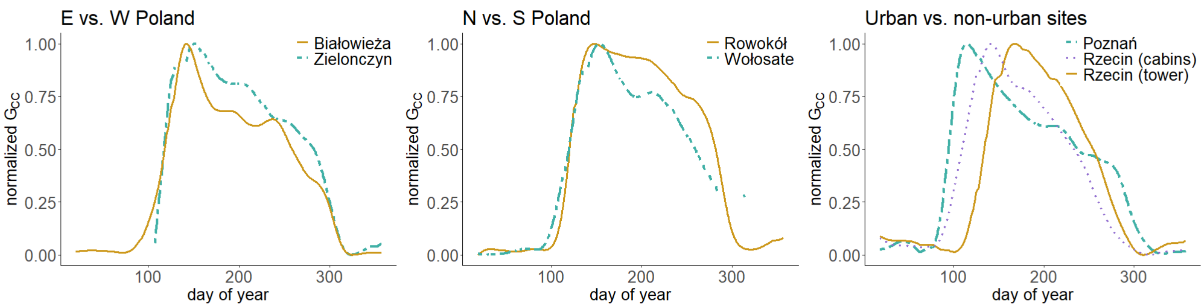


Fig. 5. Normalised green chromatic coordinates (G_{CC}) spline-fitted curves for western and eastern Poland sites (left), northern and southern Poland sites (middle), urban and non-urban sites (right)

Discussion

Seasonal RGB dynamics

Attempts to determine SOS and EOS showed that the observation method using a phenocamera is sensitive to changes in the green channel occurring anytime during seasonal growth, not only at the seasonal onsets of growth and senescence. Both trees and semi-natural plant communities (e.g., pastures or lawns) are influenced by environmental factors throughout the seasonal growth cycle, but the latter are also subject to regular anthropogenic influences (e.g., mowing) affecting observable greenness. Therefore, phenophase extraction with the method proposed in *phenopix* brought more consistent and less erroneous results for woody plants than for herbaceous plants (representing semi-natural ecosystems in this paper). This, however, does not mean that all herbaceous or graminoid surfaces are unsuitable for automated camera observations. Continuous monitoring enables the recording of changes in RGB dynamics during the growing season that can be associated with vegetation treatments (i.e., mowing, branch pruning and plant removal). Examples of the effects of mowing events on vegetation are shown in Table 3 for the

Wołosate ROIs and in Fig. 2 for the Zielonka herbaceous ROI. A substantial drop in G_{CC} values after the first G_{CC} peak, followed by a secondary increase during summer months, represents biomass removal in both cases. However, depending on species structure and timing of the treatment, SOS phenophase extraction for such ROIs can be accurate (Wołosate) or biased by those midseason G_{CC} shifts (Zielonka). An extreme case of a regularly treated lawn is the one at the Kórnik site (Tab. 3). Due to the lack of seasonal variation in green colour throughout the year, the phenophase extraction for this site was omitted.

More detailed insight into the seasonal growth of both low vegetation cover and tree canopies may be afforded by other methods of tracking changes in G_{CC} dynamics (also available in the *phenopix* package but not studied in this research) or additional parameter analysis. Thus, continuous image collection offers numerous opportunities for research, and gaps in time-series data are undesirable even during midseason G_{CC} plateaus or offseason dormancy periods. Short-term RGB shifts (lasting several days, not occurring within a single day) may reflect shifts from one phenophase to another, especially when the ROI covers an area of the plant community with substantial dominance by a single species or an individual plant. For example, analysis of all calculated RGB parameters (Tab. 2) characterising individual images, using a machine learning algorithm, already enabled the identification of the flowering periods of individual woody plants at the Poznań site of the Dendrological Garden (Różańska *et al.* 2025). Considering both the opportunity to track growing season duration and (to at least some extent) specific phenophases, camera observations become a valuable supplement to conventional phenology, which focuses primarily on recording plants' individual phenological phases (Koch *et al.* 2007; Meier *et al.* 2009; Primack *et al.* 2023).

Although phenocameras are usually installed to record the plant canopy, a rapid increase in B_{CC} (Fig. 2) emphasises broader benefits of plant canopy monitoring via digital repeat photography. There are already multiple studies on tracking snow cover (Julitta *et al.* 2014; Arslan *et al.* 2017) or fog (O'Connell, Alber 2016) in the phenocamera FoV. Here, however, the continuity of the data series is again of great importance. Even a single day of breaks in image recording may affect the results of snow cover studies, especially in regions where snow cover is short-lived and rare. Such gaps may be particularly harmful to camera observations in the lowland and western parts of Poland (Poznań, Kórnik, Rzecin), which have seen increasingly rare snow cover in recent years (Szwed *et al.* 2017; Tomczyk *et al.* 2021). In 2024, the network experienced interruptions in the operation of the university server during the winter season. Hence, the number of images showing snow cover is negligible for many sites, despite its presence during this period.

Phenological season

Körner *et al.* (2023) emphasise that the growing season can be perceived in various ways: as 1) an actual period of seasonal individual plant/plant part tissue growth; 2) a period when the whole canopy production is measured and understood as carbon uptake; 3) meteorological conditions, theoretically enabling plant development; and 4) a period when plant development is observable. The latter, referred to in the paper as the "phenological season", is the subject of both conventional phenological observations and those conducted with a phenocamera. Even though those methods focus on visible seasonal changes in plant development, they also represent very different approaches in terms of methodology and research subjects. Conventional phenology is based on selected plant species and phases, resulting in a few points (moments) in time that provide knowledge of the plant's seasonal status. On the other hand, a phenocamera can likewise serve single-date information (SOS, EOS); however, it is not limited to that. Near-continuous image recording can track phenological status throughout the entire phase and season. In this paper, the greenness curve comparisons are presented in Fig. 4. Whereas the onset of the Wołosate site's curve starts earlier than that of Rowokół, the curve peaks later, indicating longer spring leaf development at the first site. Similar differences in the pace of development occur in the Eastern-Western Poland comparison (a more sudden rise in Zielonczyn than in Białowieża) and in the juxtaposition of urban and non-urban sites, where Poznań not only starts seasonal growth earlier than Rzecin tower, but also peaks earlier than Rzecin cabins, even though its SOS is similar to that for Poznań. This confirms that one date representing SOS limits phenological information and could even be misleading, as highlighted by Inouye *et al.* (2018).

Senescence, or EOS, including leaf colouration and leaf fall, is a much more complex phenophase to observe because multiple factors affect plants' late growth stages (Kloos *et al.* 2024). This is reflected in the uncertainty estimates for the Naturevido network, for which, at many sites, EOS extends much further in time than SOS (on average 29 days vs. 8 days for woody plants and 22 vs. 8 days for herbaceous plants).

When comparing the sites presented in this research, one must not forget the differences in species composition observed across cameras. The same should be kept in mind for camera and conventional phenology comparisons. IMGW field observations mark the season onset with very early-developing species like hazel (*Corylus avellana* L.) and coltsfoot (*Tussilago farfara* L.), and the season offset with birch (*Betula pendula* Roth.), which is among the latest tree species in Poland to change the colour of its leaves and shed them (Szwed *et al.* 2025). Such methodological decisions naturally result in extending the reported duration of the phenological season, as compared to the camera method, which observes such late-growing species as oak (*Quercus robur* L., present in Białowieża) or beech (*Fagus sylvatica* L., present in Zielonczyn).

In this study, only one site's SOS overlapped with the early spring period during 2007–2021, as indicated by Szwed *et al.* (2025) based on conventional observations. The remaining locations in our study showed later development, even though 2024 was the warmest year on record in Europe. There was also no trend in the shift between IMGW-PIB results and phenocamera SOS dates.

However, including the larger group of plants in ROIs that constitute some fragments of ecosystems brings phenocamera observations into another category of phenological monitoring, which could be treated as a complementary source of data in this discipline, in addition to observations of individual plants/species. With a similar level of uncertainty to conventional observations (single observations averaged to 10-day periods for Polish IMGW-PIB data and an average of 8 days for SOS determination with phenocamera), the ability to observe such a varied species composition can be a valuable tool for analysing phenology in natural-forest provinces with distinct ecological and physiographic characteristics. In Table 1, we also included CORINE land cover identifiers, which may serve as another means of distinguishing vegetation-covered areas in the context of phenological studies. However, it should be noted that the scale of the phenocamera is more detailed than that of satellite data underlying the CORINE Land Cover data. In mosaic landscapes, such as urban and extensive farming areas, research based on satellite data is subject to errors due to data resolution. An example of this is the inaccuracy between the actual camera image and the CLC identifier, as in the case of Kórnik (an arboretum in an urban area marked as forest) or Rzecin cabins (ruderal species described as pastures). Satellite observations are, moreover, affected by clouds and aerosols, limiting the available data (Gasparovic *et al.* 2024). A phenocamera can be aimed at a small vegetation area or even a single plant; therefore, it fills the gap between more general satellite observations and precise, but discrete, conventional observations.

Frequently occurring problems and good practices: our experience

Over five years of creating and maintaining a phenocamera network, we encountered many technical and organisational issues and identified areas for improvement. The most common problem in digital repeat photography is changes in the FoV across many phenocamera time series (Seyednasrollah *et al.* 2019). The risk of frame shifting is primarily related to the presence of other devices in the camera's immediate vicinity. Calibrating or adjusting these devices may require moving the camera. Even removing the memory card when images are collected without real-time data transmission can also result in unwanted frame shifting. Tourists or even animals can also determine camera deflection. The primary guideline when installing cameras is to point them northward (Richardson 2019). However, our experience shows that even a much less favourable southward orientation (as at the Poznań site) allows for effective data collection. Therefore, the primary consideration should be to avoid unwanted movement, by positioning the camera at a safe distance from other instruments and poorly accessible areas.

Real-time data transmission enables regular image quality control, facilitating faster on-site corrections to the camera's FoV. Nevertheless, when such situations occur, a new ROI designation that most closely resembles the previous ones might be necessary. It is desirable to that any planned replacements, corrections or repairs be performed between phenological seasons to maintain a stable ROI during expected changes in RGB channels. Cooperation with the institution on whose premises the camera is installed is crucial.

Having someone on site enables fast FoV corrections or cleaning the camera lens if the view becomes blurry or obstructed by unwanted objects. Moreover, it can allow for incorporating ground observations, thereby expanding the range of image usage.

An issue worth considering at the beginning of each camera installation is its image recording schedule. If data transmission problems are suspected, it is worth reducing image resolution and increasing the frequency of uploading images to the server. Another issue is selecting the hours at which the images will be recorded. It is common practice in phenocamera research to use only hours around midday to extract RGB indices (Migliavacca *et al.* 2011; Taylor, Browning 2022). However, we recommend setting a camera timetable for a 24-hour recording schedule, if the server capacity allows for such large amounts of images. Phenocamera images serve as a site's archive, and an extensive image collection can be used in future, for methods that are yet to be developed or utilised by the phenocamera research team. It has already been shown that images from hours with a lower sun angle, which are not preferable for G_{CC} extraction in greenness curve fitting, aid in some image classification (Almeida *et al.* 2012). Nevertheless, if server resources are limited, a few photos taken during the day should be sufficient, as long as they are recorded during daytime.

Conclusions

This paper's main purpose was to present our experience in conceptualising, implementing and analysing data from Naturevido, the first Polish phenocamera network. As inexpensive and widely used devices, RGB cameras can be a valuable support for conventional, human-based phenological research. The existing infrastructure allows for easy organisation of measurement points, and the camera can also be installed in a location without access to a mains power line. The analysis is not limited to determining SOS and EOS; other changes within the camera FoV can also be measured, such as vegetation treatments, phenophases and meteorological events (e.g., snow, fog). Cameras enable observation of many plant species, entire plant communities, and individual plants at various distances from the camera and across different regions of the image. The Naturevido network, launched in 2020, enables modern observation of plant communities in Poland and confirms previous studies on the feasibility of using any RGB camera model. Woody species are more susceptible to analysis; however, a detailed image study allows us to also understand the course of greenness for the herbaceous plant cover.

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