

RESEARCH ARTICLE

Time-lapse cameras bridge the gap between remote sensing and in situ observations of tundra phenology

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Abstract

1. As the Arctic experiences continued warming, significant ecosystem changes, such as the northwards migration of woody species, are underway in tundra landscapes throughout the region. Despite these observable shifts, there remains a gap in our understanding of how climate warming impacts the phenology of tundra plants—specifically, the timing of their growth and reproductive cycles—especially across heterogeneous landscapes.
2. Measuring phenology in the Arctic is challenging, requiring observations throughout the growing season and especially early and late in the season—times when field researchers are typically absent from their study sites. While remote observations offer broad coverage across the biome, they lack the detail needed for accurate phenological interpretations and may introduce significant errors. To address this, time-lapse cameras (phenocams) present a promising solution, enabling simultaneous, individual-level observations across disparate sites.
3. In this study, we assess and present the precision, accuracy and practicality of monitoring reproductive phenology using repeat photography in tundra ecosystems by comparing satellite imagery, in situ observations and phenocams deployed on Qikiqtaruk—Herschel Island, Yukon Territory, Canada.
4. Our results show that time-lapse photography is a powerful tool to detect species-specific phenology of Arctic vegetation, with an accuracy that is similar to in situ observations conducted by park rangers across the growing season, and at a much higher spatial and temporal detail than satellite data. Especially in the remote Arctic the low cost and ease of deployment across disparate sites throughout the whole year make phenocams an important tool for observing vegetation dynamics in a changing Arctic.

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KEYWORDS

Arctic, flowering, growing season length, phenology, remote sensing, senescence, time-lapse cameras (phenocams), tundra vegetation

1 | INTRODUCTION

The Arctic is warming at four times the rate of the rest of the planet (Rantanen et al., 2022), causing widespread ecological change with far-reaching consequences for climate feedbacks, wildlife and Indigenous communities (Chapin et al., 2005; Downing & Cuerrier, 2011; Myers-Smith et al., 2019; Tape et al., 2016). Arctic vegetation change can influence biodiversity and atmospheric fluxes (Myers-Smith et al., 2020). The Arctic harbours great carbon reserves in the topsoil, the loss of which would have long-lasting negative effects on the global climate (Crowther et al., 2016; Post et al., 2019). It is also becoming increasingly clear that Arctic vegetation change is not happening in a uniform, linear manner (Assmann et al., 2020; Bjorkman et al., 2015; Collins et al., 2021; Elmendorf et al., 2012; Myers-Smith et al., 2020). Due to the changing climate, species migrate in and out of ecosystems, their traits change (e.g. taller stems) and their phenology shifts (Bjorkman et al., 2018; Sistla et al., 2013). Plant phenology, the timing of life events such as *first leaf*, *first flower* and *petal shed*, is one of the most widely observed consequences of climate warming (Cleland et al., 2007). Changes in phenology can affect reproductive success and carbon sequestration as well as cause potential mismatches with pollinators or herbivores (Bjorkman et al., 2015; Collins et al., 2021; Inouye, 2022). Short Arctic growing seasons mean plants can be sensitive to impacts from even small shifts (Boyle et al., 2022; Myers-Smith et al., 2020).

Historically, ecological observations have mainly occurred on two different scales, from localized in situ observations to expansive global satellite imagery (Levin, 1992; Wiens, 1989). This disparity introduces significant gaps in our understanding of Arctic ecosystems. Differing scales of measurement may also detect ecological processes differently (Anderson, 2018; Estes et al., 2018) and ecosystem function and service delivery (Raudsepp-Hearne & Peterson, 2016), skewing or obscuring conclusions. While individual-level observations provide detailed insights, they are limited by logistical constraints and the short growing season for collecting data (Metcalf et al., 2018; Sagarin & Pauchard, 2010). Logistical challenges of the Arctic, with low human population densities—sparse and mostly along coastlines—have led to low spatiotemporal coverage of observations relative to temperate regions. In situ observation is often clustered around logistical centres, such as human settlements and existing research infrastructure (López-Blanco et al., 2024; Metcalfe et al., 2018). These logistical centres are not evenly distributed and recent geopolitical events have worsened the bias in Arctic data collection even further (López-Blanco et al., 2024). In situ observation allows the closest inspection of vegetation *phenophases*, the different stages of plant growth and reproduction including bud burst, flowering, pollen development and leaf senescence. These observations require a field observer throughout the growing season, but

unsteady snowpack and unreliable weather conditions often prevent data collection early and late in the season. There are clear indicators, however, that these understudied late- and early-season phenophases are most sensitive to changing climatic conditions (Cooper et al., 2011; Pearson et al., 2013; Rixen et al., 2022).

Global-scale satellite imagery offers broad coverage, but may miss critical fine-scale processes, such as detecting flowering times of different species (Kennedy et al., 2014; Metcalfe et al., 2018). Arctic vegetation is monitored through many different remote sensing methods, ranging from publicly available time-series of satellite imagery, such as Sentinel, Landsat, Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) platforms, as well as the recent developments in Unmanned Aerial Vehicles (UAVs) and commercial satellites with higher spatial resolutions (Beamish et al., 2020). Despite the wide availability of remote sensing data, however, the utility of these data in Arctic regions is often limited by high cloud cover, low sun angles and challenges distinguishing specific species (Beamish et al., 2020; Stow et al., 2004). These limitations can mean no remote sensing data are available across an area of interest for the entire growing season.

Time-lapse cameras (hereafter phenocams) have the potential to bridge the gap between in situ observations and remote sensing. In forests and grasslands, time-lapse imagery has established use in studying vegetation greenness effectively, when compared to in situ observations (Browning et al., 2017; Melaas et al., 2016). RGB cameras have been tested on Svalbard to derive vegetation greenness indices in plots with differing vegetation composition, with similar results to satellite-derived greenness (Anderson et al., 2016) and monitor moss hydrology through reflectance (Graham et al., 2006). Even in High-Arctic Northeast Greenland and Alaska, cameras have been shown to accurately observe green-up, peak greenness and senescence when compared to ecosystem productivity indices from flux towers (Richardson et al., 2007; Westergaard-Nielsen et al., 2017). Several networks are collecting time-lapse imagery to create large, spatially distributed and long-term datasets (Brown et al., 2016), such as the Phenocam Network (Richardson et al., 2018). Machine learning methods are increasingly used to automate these images' analysis (Almeida et al., 2014). Identifying single species in optimal conditions (e.g. no confounding similar-coloured species in view) has been demonstrated with machine learning algorithms (Mann et al., 2022). However, these rapidly developing semi-automatic methods have not yet been effective enough to detect flowering phenology of multiple individual species within the tundra biome (Anderson et al., 2016; Julitta et al., 2014; Sellers et al., 2023). A similar study for grassland vegetation showed the potential of using time-lapse cameras for capturing flowering phenology, while showing limitations in distinguishing between similar species, and

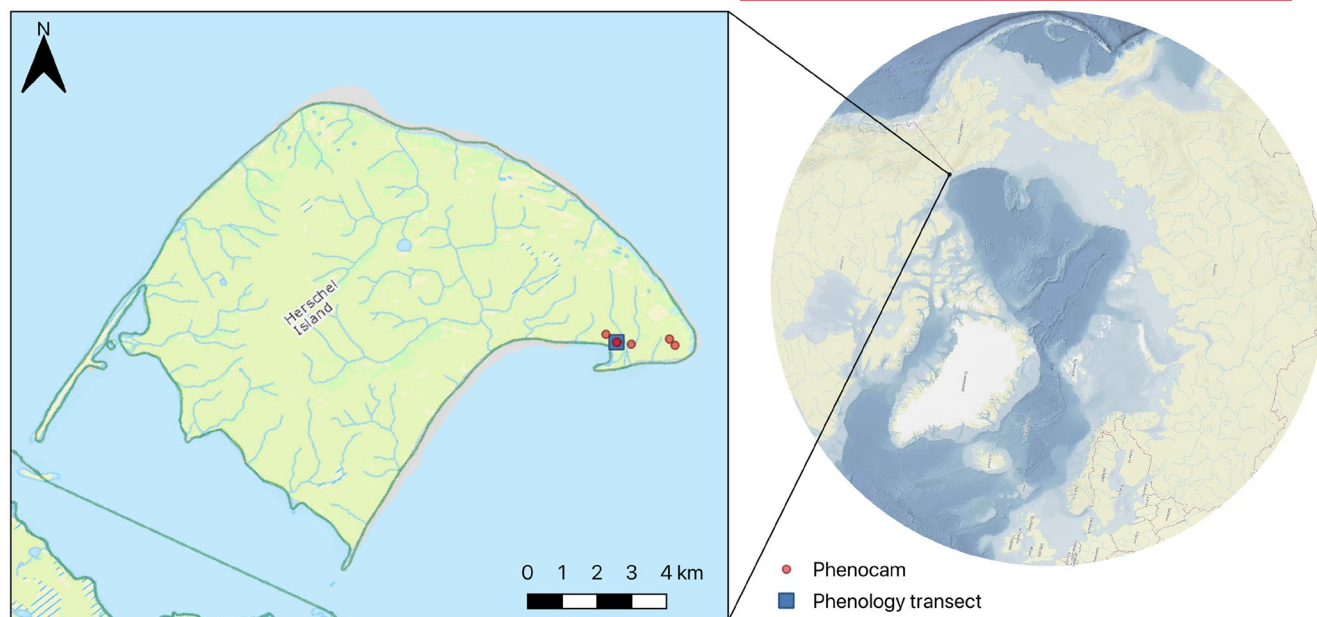


FIGURE 1 Location of our phenocams and in situ observations on Qikiqtaruk–Herschel Island.

difficulties including enough images of rare species for automatic classification (Andreatta et al., 2023).

With increased monitoring and understanding of Arctic vegetation dynamics needed, and new methods and datasets emerging, we quantify the strengths and weaknesses of time-lapse imagery to bridge the gap between in situ observations and remote sensing in the Arctic tundra. Here, we present a method of standardized manual detection of leaf and flowering phenology using time-lapse cameras. We compare the performance of this method for observing vegetation growth and species-specific flowering phenology from time-lapse imagery to in situ observation and satellite data on coverage and precision.

2 | METHODS

Our focal field site is Qikiqtaruk–Herschel Island (69.6°N, –138.9°E), Yukon Territory, Canada. Underlain by ice-rich permafrost, Qikiqtaruk has a maximum elevation of 183 m (Burn & Zhang, 2010). The island's overall vegetation type is 'moist acidic shrub tundra,' with two distinct vegetation communities found where our phenology observations were recorded: (1) 'Herschel' vegetation classification, characterized by *Eriophorum vaginatum* tussocks and *Salix pulchra* canopies, and (2) 'Komakuk' vegetation classification, characterized by forb species (e.g. *Dryas integrifolia*, *Lupinus arcticus*), mosses, grasses, the willow species *Salix arctica* and *Salix glauca* (Myers-Smith et al., 2011; Myers-Smith & Hik, 2013). These communities are spatially controlled by microtopography, soil microenvironment and physical disturbance and our in situ observations are distributed across these heterogeneous conditions (Obu et al., 2017). Park rangers and scientific researchers are present each year during the summer season.

We use in situ phenology monitoring data from 2016 to 2019 from Qikiqtaruk, following the International Tundra Protocol (ITEX) detailed by Molau and Molgaard (1966). Three species (*Dryas integrifolia*, *Eriophorum vaginatum* and *Salix arctica*) are monitored every growing season along 50 m long transects, containing 20 marked individuals in 10 locations or 10 plots of 10 × 10 cm along the transect, depending on the species. These observations are made approximately every 3 days throughout the summer by rangers (Myers-Smith et al., 2019).

We installed a network of six phenocams across a 2 × 2 km area, spanning environmental and vegetation gradients (Figure 1). We used *Wingscapes TimelapseCam Pro* cameras, manufactured by Moultrie (Georgia, USA), attached to sturdy metal tripods (of various brands) 1 m above the ground. The cameras were aimed northwards at a slight downward angle to avoid low sun angles and prevent glare, allowing the cameras to capture snowmelt timing and landscape greenness throughout the growing season. The cameras' field of view shows approximately 2 m² of ground surface in enough detail to identify plant species and phenophases (Figure 2).

We programmed each camera to capture one photograph per hour at infinite focus and the highest resolution possible (20 MP). We recorded each camera's location using a Garmin hand-held GPS device or GNSS device. Installation took place at the beginning of the growing season between 2016 and 2019, and cameras were maintained for as long as possible across subsequent years, though some were disturbed by wildlife or experienced mechanical failures. We processed the image data for all cameras according to the following workflow. (1) We assessed the quality of the photos and added a quality marker, indicating different issues, that is, fog, water on lens, fallen camera, too dark or lens flare. We used images from 1 year of one phenocam (Phenocam 6, 2018) to first assess how three different persons determined image quality. Each

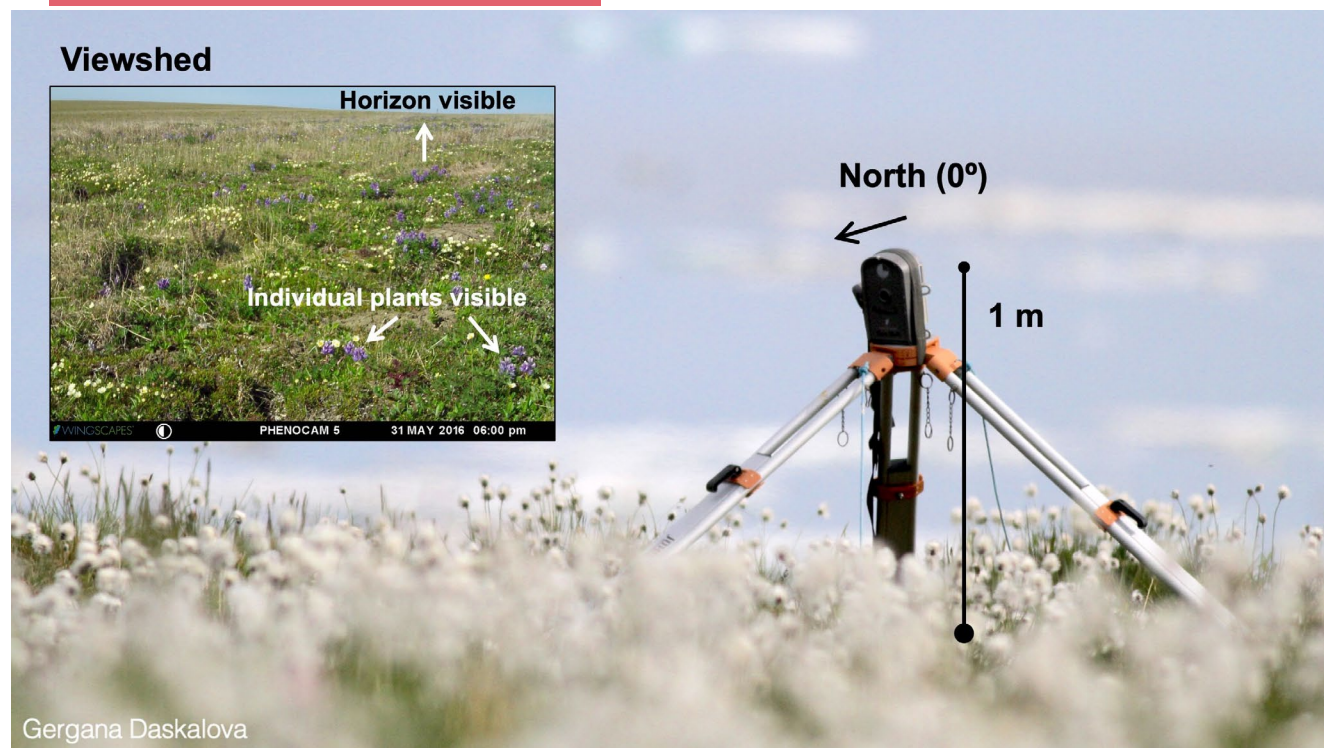


FIGURE 2 Phenocam set-up on Qikiqtaruk, inset showing an example time-lapse image taken by the camera. Photo: Gergana Daskalova.

person assessed all images and between three persons an average of 90% of images were classified exactly similarly. This was similar enough to divide the quality classification of all images over different persons following the same protocol without additional checks. (2) We then removed all unusable images flagged in the quality control process to only analyse high-quality images. The percentage of remaining usable images per camera ranged from 50% to 66% of all images recorded, except for phenocam 6 where only 28% of images could be used. On average 59% of all recorded images during this study could be used. Water on the lens and darkness were the most common reasons for unusable data. As the cameras are programmed to take photos around the clock, nighttime images were also collected. (3) We sequentially browsed all retained images for each plot and recorded the day-of-year (DOY) for the first occurrence of each phenophase detailed in the ITEX protocol (e.g. leaf bud visible, leaf bud burst, first flower), to match with the in situ monitoring (Molau & Molgaard, 1966). In accordance with the ITEX protocol, we calculated the overall length of the growing season by subtracting the DOY for *Salix arctica* Phenophase 2 (first leaf bud-burst) from Phenophase 5 (last leaf green).

For each phenocam location, we extracted a time series of NDVI (Normalized Difference Vegetation Index) values for the same years as in situ and phenocam data were collected, 2016–2019. NDVI values are based on multispectral data from the Sentinel-2 mission, using the Near InfraRed (NIR) and red (R) bands, at 10m resolution and with a revisit time of every 3–4 days in perfect conditions (Drusch et al., 2012). We additionally calculated NDVI based on MODIS data, (250m resolution, 1–2 days revisit time). NDVI is commonly used

to describe vegetation phenology, here resulting in a time series of greenness throughout the season. Additionally, we calculated Normalized Difference Greenness Index (NDGI) based on MODIS data, a newer and less commonly used vegetation index based on the green, red and NIR bands, that outperforms NDVI in tundra environments (Yang et al., 2019). The Normalised Difference Snow Index (NDSI) was also calculated using the normalized difference between the green (G) and shortwave infrared (SWIR) bands to determine growing season length based on the absence of snow. We used Google Earth Engine (Gorelick et al., 2017) to access Sentinel-2 and MODIS data and calculate and extract NDVI, NDGI and NDSI values. These data were cleaned by removing observations with clouds and shadows according to Sentinel's own provided algorithms, resulting in 49% unusable images. Due to regular cloud cover and a low sun angle the intervals between usable data points are typically longer than the revisit times listed. The revisit time of Sentinel-2 for the 2016–2019 period at our phenocams' location averaged 10.2 days, with a standard deviation of 37.8. Excluding missing data during fall, winter and spring the average revisit time during the main growing season becomes 4.3 with a standard deviation of 4.2.

We used the 'lme4' package (Bates et al., 2025) in R to compare the timing (DOY) of each phenophase between the phenocam and in situ observation types. 'Year' was included as a random effect in the models to account for the non-independence of observations conducted within the same year. We determined whether the observation types gave significantly different estimates of phenological timing by comparing our full model: $DOY \sim obs_type + (1 | Year)$ to the reduced model: $DOY \sim 1 + (1 | Year)$ using a likelihood ratio test,

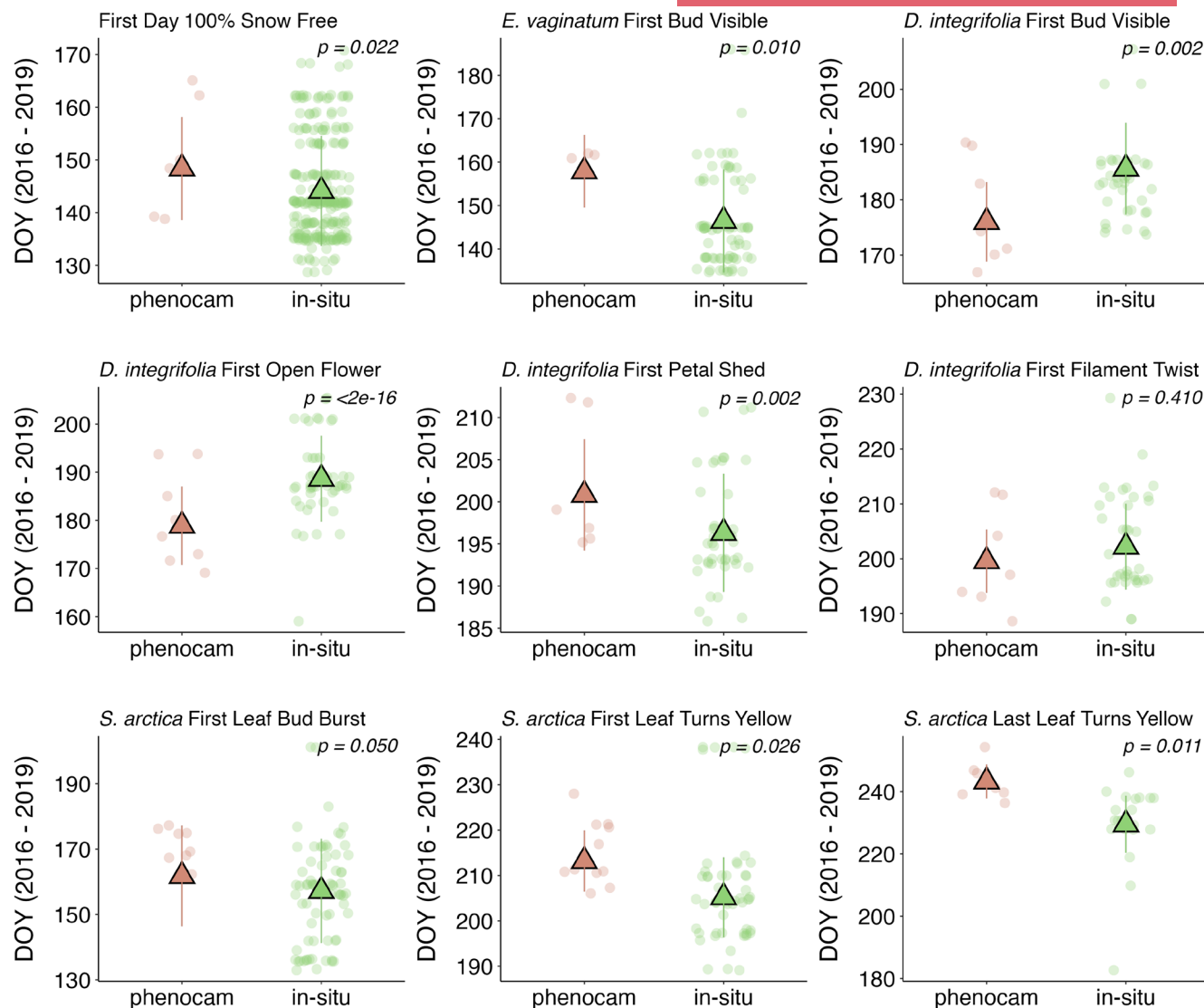


FIGURE 3 A comparison of the dates recorded for in situ observations versus observations derived from phenocams shows a tendency for the phenocam observations to be slightly later than the in situ observations, except when observing *D. integrifolia*, where the phenocams on average detect the phenophase before the in situ observation. The top row represents snowmelt and *Eriophorum vaginatum* phenophases, the middle row represents *Dryas integrifolia* phenophases and the bottom row represents *Salix arctica* phenophases. Coloured dots represent raw (observed) data, triangles and vertical lines represent the mean and 95% credible intervals of the hierarchical model.

calculating the chi-squared statistic and the p -value for each paired observation and phenophase. All analyses were performed in R version 4.4.1.

3 | RESULTS

Both in situ and phenocam observations detected *Salix arctica* leaf bud burst within the same time range, but we found significant differences ($p < 0.05$) between observation methods for all other species and phenophases. Phenophases were on average observed 9 days earlier using in situ observations when compared to phenocams, except for *Dryas integrifolia*, where instead phenocams had earlier observations relative to in situ observations in three out of four phenophases (Figure 3, Table 1). The largest discrepancies

were shown for *Eriophorum vaginatum* bud appearance at a 14-day delay between the average date of observation from in situ to the phenocam observations. At the end of the growing season, phenocams were also notably able to register the last yellow leaves of *Salix arctica* later than the in situ observations.

When comparing both methods for all phenophases included in this study in Figure 4, we see that there is a predictable, consistent difference in DOY between phenocam and in situ observations per species regarding whether the phenocam is earlier or later in detecting the phenophase. This provides the possibility of combining the installation of phenocams with in situ observations for one season, to then extrapolate those differences over the following seasons where phenocams are still deployed. However, not all phenophases were able to be detected by the phenocams, as is also visible in Figure 4.

TABLE 1 Average number of days difference between phenocam and in situ observations for 2016 to 2019.

Species and phenological stage	Mean difference DOY	SD DOY
100% snow free	7	10.4
<i>E. vag.</i> bud appearance	14	8.1
<i>D. int.</i> bud appearance	-5.7	8.6
<i>D. int.</i> open flower	-8.1	9.1
<i>D. int.</i> petal shed	5.1	7.4
<i>D. int.</i> twisting of filaments	-3.1	9.2
<i>S. arc.</i> leaf bud burst	12.3	11.2
<i>S. arc.</i> first leaf yellow	8.7	9.8
<i>S. arc.</i> last leaf yellow	13.8	10.5
Mean	4.9	9.4

Note: Positive numbers indicate how many days later the phenocams observed the same phenophase as the in situ observations. Negative numbers indicate that the phenocams registered the phenophases earlier than the in situ observations. The difference in which method detects the phenophase first varies, with the phenocams detecting phenophases earlier than in situ observations for *D. integrifolia* and later for other phenophases.

The peak in greenness during the height of the growing season was not as clearly visible in the MODIS data as in the Sentinel-2 data, and MODIS also indicated delayed green-up and senescence signals relative to the Sentinel-2 data (Figure S1). We found correspondence between increased NDVI in Sentinel-2 data and the snow-free date extracted from the phenocam images (Figure 4). However, the number of days delay between the satellite registering NDVI values (i.e. snow-free) and first snow-free images on the cameras varied greatly between the years observed (Figure 4 and Table 2). For senescence, we cannot draw clear conclusions on whether phenocams or in situ observations align better with satellite data, since the NDVI values remain high until the end of the snow-free season. Additionally, the start of the growing season and onset of senescence as shown by the NDVI signal from Sentinel-2 coincided closely with the Normalized Difference Snow Index (NDSI) from the Sentinel-2 sensor, although NDSI is harder to interpret than NDVI due to lingering snow patches obscuring the signal (Figures S2). The Normalized Difference Greenness Index (NDGI) showed greater variation between years than NDVI, but worse correspondence to the phenocams (Figures S3; Figure 5).

4 | DISCUSSION

We found that the visibility of certain phenological events contributed to their accurate detection across in situ, phenocam and satellite observations. Thus, the required level of detail for a study should dictate what viewshed phenocams should have in order to capture that detail. The setup of phenocams in this study allows for both landscape greenness and flowering phenology

to be studied. Here we chose to solely focus on flowering and leaf phenology to compare with the high level of detail in in situ observations.

4.1 | The phenocam viewshed influences the precision of phenology observations

The choice of how to place the phenocams with regard to the vegetation also influences which phenophases can be observed from the images. In this study, the phenocams were placed with a landscape view, allowing for species identification close to the camera, as well as a landscape greenness observation. Other studies have placed phenocams facing directly downwards, focusing on a few individual plants only, or insect visits to flowers (Bjerge et al., 2024; Mann et al., 2022). This provides great detail, though without landscape context. However, vertical placements may allow for increased detection of certain phenostages. Buds bursting from a tussock can for example be observed in situ, then registered significantly later by phenocams, only once they have emerged further and almost open into flowers (i.e. the following phenophase). Conversely, phenophases characterized by more conspicuous features, such as the twisting of filaments in *Dryas integrifolia*, or opening of flowers, exhibited the most consistent observation dates between phenocam and in situ observation, with no significant delay between the two methods. The in situ observations and phenocam viewsheds did not fully align in this study, due to the high variation in topography, so part of the variation between the two methods could also be attributed to simply not looking at the same individual plants, but rather different individuals of the same species within the nearby landscape.

4.2 | Phenocams are especially useful for observing senescence

Phenocams allowed for a continuous observation of the ongoing senescence of different species, for the total length of the growing season, until the vegetation was covered by snow, thereby providing more detail than either the in situ observations, which registered only the onset of senescence due to logistical and weather constraints prohibiting people from being present until the end of the season, or NDVI, where species-level information is missed. While green-up was observed later in Sentinel-2 data than by in situ observation or phenocams, the delay is similar across the different years and could be calculated into a landscape-specific 'offset'. Using NDVI for measuring senescence is especially challenging in the tundra, largely due to high variation among plant species and types, for example, lichens and shrubs (Nelson et al., 2022). Onset of senescence, marking the conclusion of the NDVI greening curve, is harder to compare to phenocam data, as there is a more gradual decline of vegetation activity and fewer phenophases were tracked in the late season than during the spring.

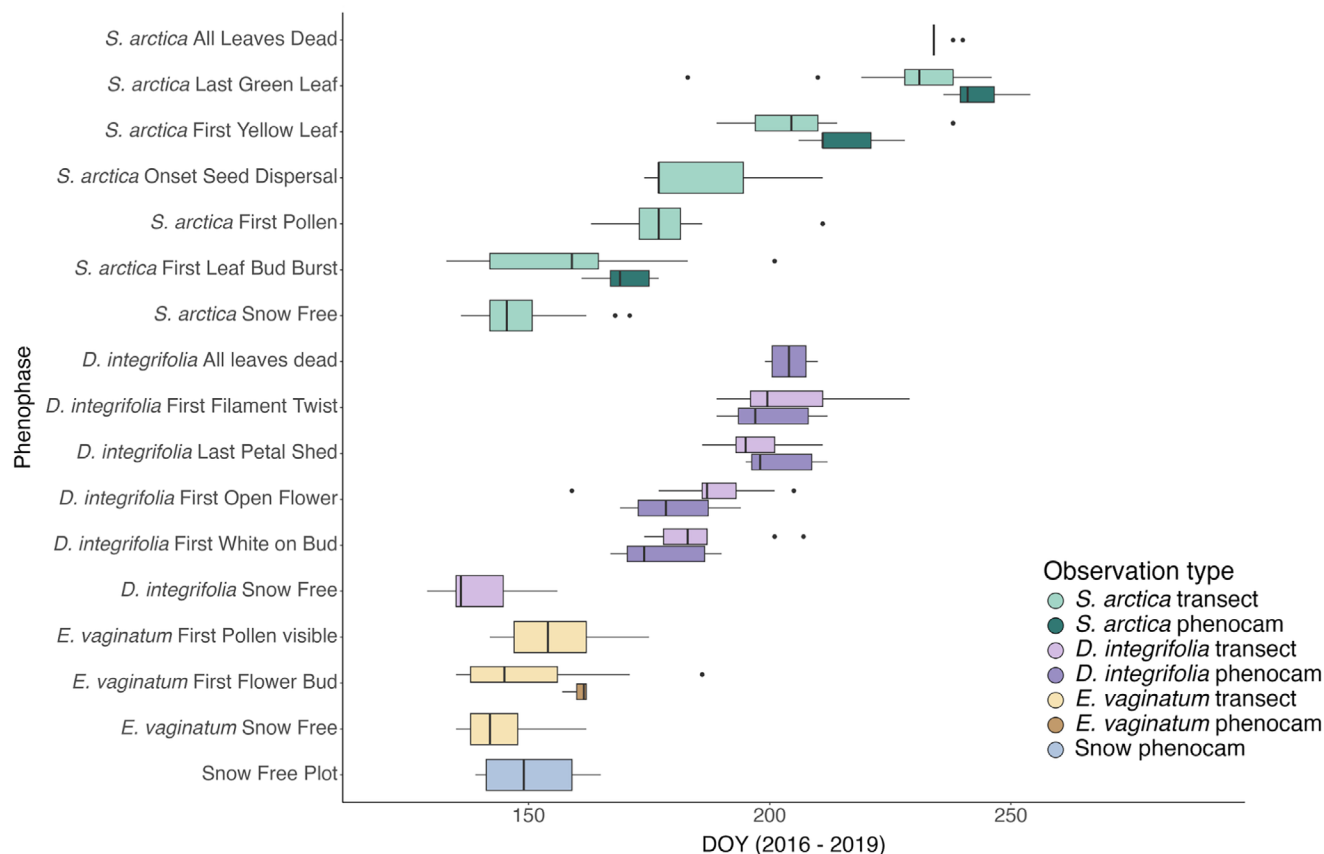


FIGURE 4 Alignment between phenocam and in situ observations chronologically throughout the growing season (raw data). Boxplots represent the range of dates in which distinct species phenophases take place throughout 2016–2019, with phenocam observations in the darker boxes and in situ observations in the lighter boxes. Phenocam and in situ observations align well throughout the growing season with relatively consistent differences between the two methods per species.

TABLE 2 Number of days' difference between the average snow-free dates for the phenocams and the satellite observations. The magnitude of the delay of the satellite NDVI signal compared to the phenocams observing the first phenophase varies among years.

Year	2016	2017	2018	2019
DOY phenocams	131	129	153	133
First DOY NDVI	138	149	162	187
Difference in days	7	20	9	54

4.3 | Phenocams provide high temporal and spatial coverage at a low cost

Leveraging phenocams for extended observation periods beyond the traditional field season can offer a valuable means to fill knowledge gaps and enhance understanding of late-season dynamics (Anderson et al., 2016; Beamish et al., 2018; Browning et al., 2017). It remains costly and logistically challenging to have humans observing phenology in situ, leading to datasets limited to the growing season's most active times and locations around research centers which provide logistical support

(Metcalf et al., 2018). Arctic landscapes in particular become more challenging to navigate at the start and end of the snow season, when snow is patchy and unreliable for skis, vehicles or hikes. Once snow has accumulated or before it has melted, plant phenophases are not observable; however phenocams are very useful for capturing snowmelt and snow return and subsequent early or late season phenophases. Phenocams have the potential for great spatial and temporal coverage at low cost, as they can be deployed in high numbers and do not require regular visits.

Phenocams, once installed, can take images at predetermined intervals throughout the year. Logistics often limit in situ observation to a 2- to 3-day revisit frequency. Human in situ observations may also be prone to observer error (Morrison, 2016), while digital imagery allows for data to be saved and observations to be more reproducible (Anderson et al., 2016; Beamish et al., 2018; Browning et al., 2017). Satellite remote sensing can cover the whole Arctic region, even the most remote areas, which makes it a valuable complement to observing phenology at lower spatial scales (Nelson et al., 2022). The temporal frequency of satellite remote sensing depends on the instrument and weather. Here, we used Sentinel-2 and MODIS data which provide a maximum temporal revisit frequency of 3–4 days in the Arctic. However, the Arctic also has very frequent low cloud cover, decreasing data

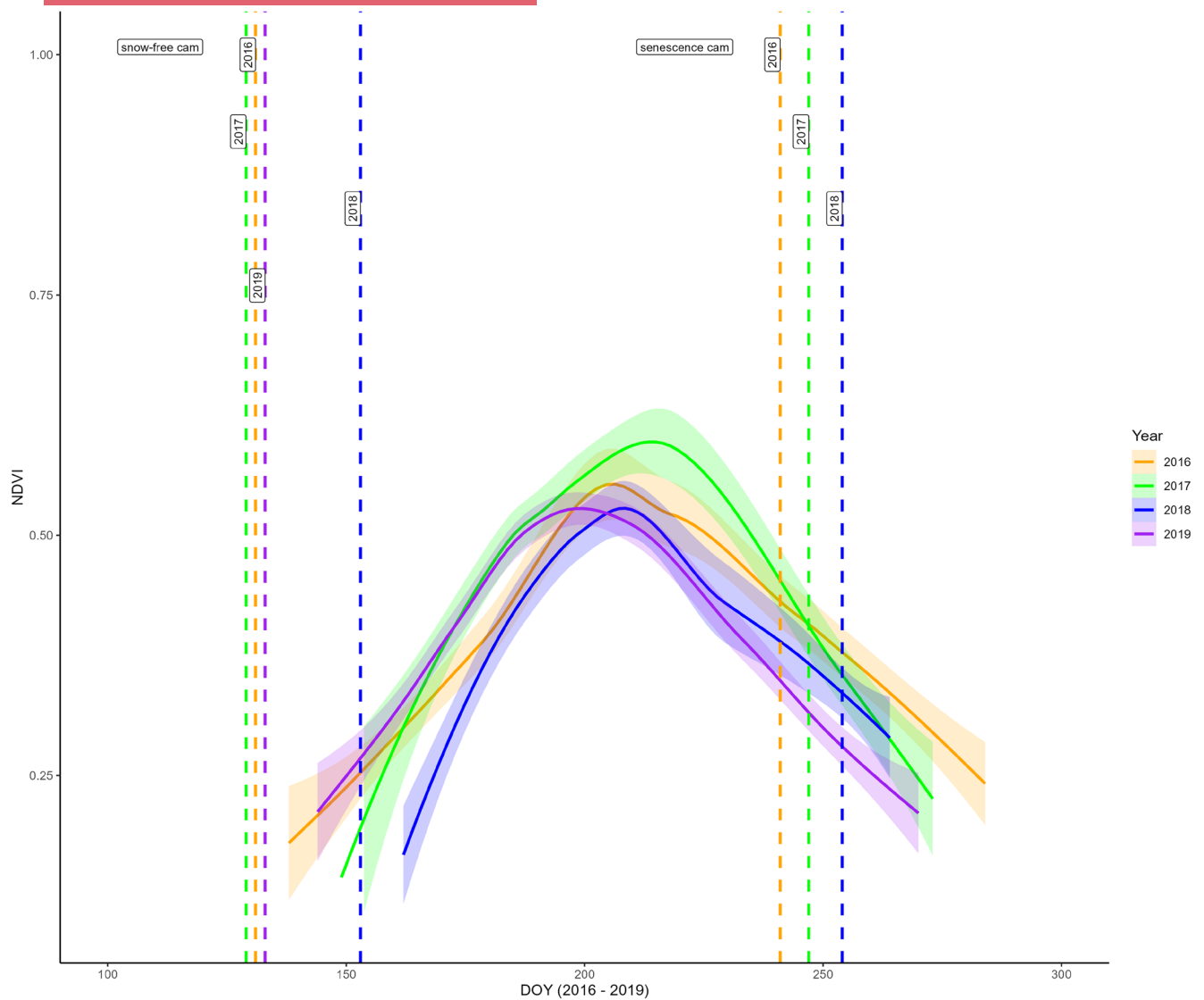


FIGURE 5 Comparison between Normalized Differential Vegetation Index (NDVI) and average dates of snowmelt and leaf senescence for the same locations as the phenocams in each year. The satellite-derived NDVI signal was delayed when compared to the phenocams for all years included in this study, and during the start of the season there is no usable satellite coverage. The curved solid lines represent NDVI values as observed by Sentinel-2 in each year over the duration of the growing season, while the vertical dashed lines represent the average phenocam-observed snow-free date (left side) or date of leaf senescence, represented by last yellow leaf of *Salix arctica* (right side) in each year. This phenophase was not available from the phenocams in 2019, as the cameras were not downloaded until later and therefore not available during the analyses for this study.

collection frequency considerably. Combined with short growing seasons causing rapid vegetation changes (especially in the early season), much detail can be missed (Beamish et al., 2020; Stow et al., 2004). A researcher with bad luck could be without any usable data for a whole growing season. Sentinel-2 has much higher spatial resolution at 10m than MODIS at 250m, more accurately representing highly heterogeneous landscapes like the Arctic (Stow et al., 2004). The main benefit of satellite remote sensing for observing Arctic phenology is the freely available data, extensive spatial coverage, with the potential for longer time series. However, comparing satellite data with in situ observations and phenocams allows for more meaningful ecological interpretations of plant phenological change over time, as previously shown for

other biomes (Brown et al., 2016; Browning et al., 2017; Julitta et al., 2014; Richardson et al., 2018). As such, it remains an incredibly valuable tool for studying vegetation change especially in the Arctic.

4.4 | Risks associated with only using phenocams

Using phenocams as the only source of data collection on vegetation phenology risks missing both inconspicuous species as well as discerning species that can only be distinguished by studying details up close. Our proposed method utilizes phenocams in conjunction with at least a vegetation survey carried out in situ

to register which species are present within the viewshed of the cameras. Further risks of using phenocams for data collection are errors in the set-up of the cameras, resulting in, for example, different focus lengths and differently sized viewsheds between cameras, as well as forgetting to turn the camera on completely after installing. Cameras can also fail due to batteries running out earlier than expected, water damage due to heavy rains, and wind or wildlife knocking over cameras, causing data gaps. Thus, regular check-ups of the phenocams are recommended, as well as using sturdy tripods for setup and additionally fastening the tripods with wires and tent pegs in exposed areas. Most of these risks can be mitigated by merely scaling up the number of phenocams used in a study, creating redundancy by increasing numbers. Here we do not aim to promote phenocams as a single method over others on all bases, but merely show the utility of this emerging method. There are considerable scientific gains that can be made through using phenocams, especially when used together with other methods, such as in situ observations.

5 | CONCLUSION

This study shows that phenocams are a reliable observation method to monitor Arctic vegetation phenology. Phenocams can bridge the gap between in situ observation and satellite data and increase spatial and temporal coverage. Phenocams provide observation at great phenological detail, especially for conspicuous species, such as *Dryas integrifolia*, at low cost and with the opportunity to save image data for re-interpretation or other analyses in the future. We outline the benefits and weaknesses of the different observation methods for the Arctic biome as found in this study, allowing researchers to make informed decisions about method selection for different purposes.

Phenocams provide the potential of observing Arctic vegetation phenology at high spatial and temporal resolution that can be scaled up geographically at low cost, making it available for stakeholders and researchers with varying budgets, to improve the observation of vegetation phenology especially in remote Arctic biomes. Data collected through the use of phenocams can be saved and re-interpreted to allow for time-series analysis and protect against single observer bias. We recommend using phenocams mainly in conjunction with in situ observation, as individual plants and smaller, inconspicuous species cannot always be accurately studied using solely phenocams.

AUTHOR CONTRIBUTIONS

Geerte Fälthammar de Jong, Elise Gallois, Joseph S. Boyle and Maude Grenier conceived the ideas and designed methods, with support from Isla H. Myers-Smith and Anne Bjorkman; Elise Gallois and Isla H. Myers-Smith collected the camera data, Maude Grenier supported logistically; the in situ data were collected by Inuvialuit Park Rangers as a part of the Qikiqtaruk–Herschel Island; Geerte Fälthammar de Jong collected remote sensing data; Geerte Fälthammar de Jong, Elise Gallois, Joseph S. Boyle and

Maude Grenier analysed the data; Geerte Fälthammar de Jong led the writing of the manuscript; Geerte Fälthammar de Jong, Elise Gallois, Joseph S. Boyle and Maude Grenier wrote sections of the manuscript; all authors contributed revisions and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors report that there are no conflicts of interest.

PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/2041-210X.70188>.

DATA AVAILABILITY STATEMENT

Data available via <https://doi.org/10.5281/zenodo.17338741> (Fälthammar-de Jong et al., 2025).

STATEMENT ON INCLUSION

Our study has been executed by early career and senior researchers from a number of different countries and different institutes, one of which is based in the country where the study was carried out. All authors were engaged early on with the research and study design to ensure that the diverse sets of perspectives they represent were considered from the onset. We include and recognize the knowledge of Indigenous people who contributed to the phenology monitoring through the Qikiqtaruk–Herschel Island Ecological monitoring programme published in the paper Myers-Smith et al., 2019 and co-authored by Inuvialuit Park Rangers from Qikiqtaruk–Herschel Island Territorial Park.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. NDVI data from the MODIS satellite sensor show a delayed response to green-up and senescence when compared to phenocam data.

Figure S2. NDSI data from Sentinel-2 show good correspondence to phenocam observations of snow-free growing season length, but lingering snow patches make the signal less clear to interpret.

Figure S3. NDGI data from Sentinel-2 show worse correspondence than NDVI to phenocam-based start-of-season data.

Table S1. Description of phenophases included in the study.

Table S2. Description of spatial resolution, temporal resolution and accuracy of each monitoring system for the Arctic.

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