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Review

Plugging the Gaps in the Global PhenoCam Monitoring of Forests—The Need for a PhenoCam Network across Indian Forests

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Abstract: Our understanding of the impact of climate change on forests is constrained by a lack of long-term phenological monitoring. It is generally carried out via (1) ground observations, (2) satellite-based remote sensing, and (3) near-surface remote sensing (e.g., PhenoCams, unmanned aerial vehicles, etc.). Ground-based observations are limited by space, time, funds, and human observer bias. Satellite-based phenological monitoring does not carry these limitations; however, it is generally associated with larger uncertainties due to atmospheric noise, land cover mixing, and the modifiable area unit problem. In this context, near-surface remote sensing technologies, e.g., PhenoCam, emerge as a promising alternative complementing ground and satellite-based observations. Ground-based phenological observations generally record the following key parameters: leaves (bud stage, mature, abscission), flowers (bud stage, anthesis, abscission), and fruit (bud stage, maturation, and abscission). This review suggests that most of these nine parameters can be recorded using PhenoCam with >90% accuracy. Currently, Phenocameras are situated in the US, Europe, and East Asia, with a stark paucity over Africa, South America, Central, South-East, and South Asia. There is a need to expand PhenoCam monitoring in underrepresented regions, especially in the tropics, to better understand global forest dynamics as well as the impact of global change on forest ecosystems. Here, we spotlight India and discuss the need for a new PhenoCam network covering the diversity of Indian forests and its possible applications in forest management at a local level.

Keywords: phenology; Indian PhenoCam; forest management; long term monitoring

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1. Phenology as an Indicator of the Impact of Climate Change on Forests

Phenology is the science that deals with the study of recurrent events in the biological lifecycle and how these lifecycle events are influenced by temporal changes in biotic and abiotic factors [1]. Plant phenology indicates significant seasonal events, such as sprouting, leaf development, flowering, fruiting, and leaf fall in a plant's life cycle, which influences ecosystem functions via controlling energy and carbon through interactions between the atmosphere and plant communities [2–4]. The climate is the major controlling factor (temperature, water availability, and day length), although non-climatic parameters, such as altitude, slope, shadings, soil properties, and nutrient availability, may also affect plant phenology [5,6]. The responsiveness of phenology to the annual variability in weather parameters serves as an essential indicator of climate change in terrestrial ecosystems [2,7]. Multiple studies across the globe have confirmed the impact of climate change on plant phenology, such as advanced spring greenup [8,9], delayed senescence [10,11], and a shift in flowering and fruiting [12]. The shift in phenological timing has affected atmosphere–vegetation interactions, the land surface energy balance, vegetation productivity, the water cycle, and the global carbon cycle [2,13]. The increasing length of the growing season (LOS) has generally resulted in an increased uptake of CO_2, potentially increasing the annual net primary productivity (NPP) [14]. However, the NPP also shows a negative trend with an increasing LOS due to increasing temperature during the growing season, resulting in increased respiration [15]. A longer LOS and increasing air temperature may also affect plants' transpiration rates, which influences the global water cycle [16]. In addition, the shift in phenological parameters can also affect agriculture, human health, and forestry. For example, on a global scale, approximately 27% of cereal crop regions have experienced a longer LOS (2.3 days per year) since 1981, affecting food production in these areas [17]. Similarly, the increasing LOS has also affected processes related to the phenology of wood formation [18]. Thus, monitoring the phenological dynamics of vegetation is important for understanding the behavioral responses of the Earth's ecosystems to future climate change.

2. Methods for Monitoring Phenology

Phenological monitoring methods can be classified into three types based on the spatial coverage of monitoring as follows: the species level, plot-regional level, and regional-global level (Figure 1). A human observer has traditionally monitored individual organisms to visually document changes in forest phenological parameters [2]. This method of collecting plant phenological data is known for its long temporal resolutions, enabling the availability of data from the 1900s in multiple locations worldwide [19]. However, it is worth noting that the spatial distribution of these data is currently limited to a few countries, primarily including the USA (National Phenology Network, Budburst, and National Ecological Observatory Network), Canada (Nature Watch), Sweden (Swedish National Phenology Network), Russia (Chronicles of Nature), Australia (Climate Watch), Pan European Phenology database (PEP725) and the UK (Nature's Calendar). Despite these efforts, ground-based phenological observations face certain limitations, such as being constrained to a limited number of species, being more prone to human errors, requiring significant labor, and being time-consuming [20,21].

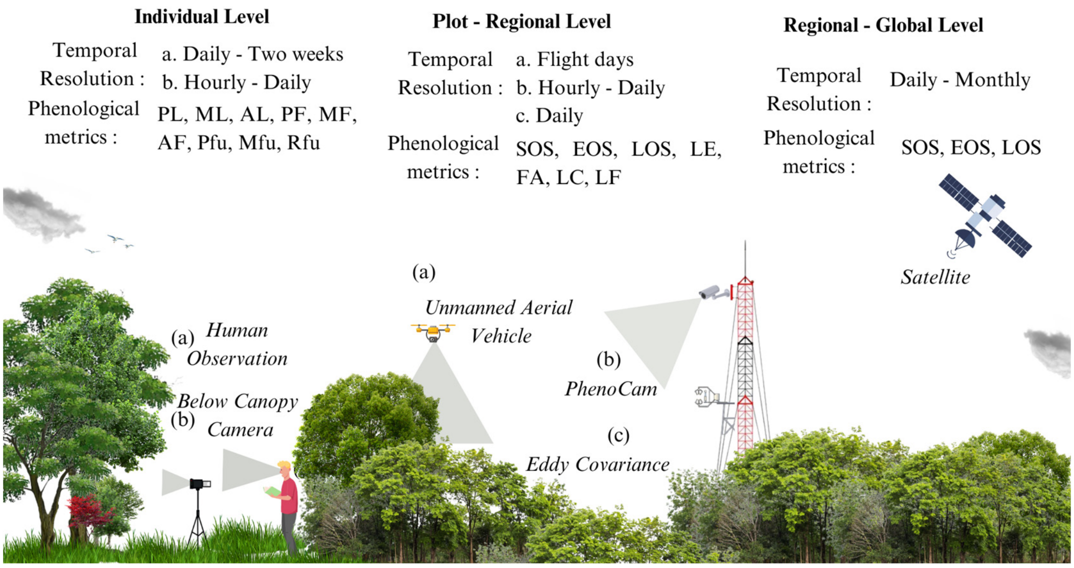

Figure 1. Overview of different methods of phenological monitoring. (Individual level: PL: production of young leaves, ML: maturation of leaves, AL: abscission of leaves, PF: production of young flowers, MF: maturation of flowers, AF: abscission of flowers, Pfu: production of young fruits, Mfu: maturation of fruits, Rfu: ripening of fruits; plot-regional level: SOS: start of season, EOS: end of season, LOS: length of season, LE: leaf expansion, FA: flower appearance, LC: leaf coloring, LF: leaf fall).

Since the 1970s, satellite-based remote sensing has introduced new possibilities for worldwide phenological surveillance at the landscape scale with the advantage of continuously collecting data for large areas. Land surface phenology (LSP) is the term generally used to represent vegetation phenology derived using satellite-based remote sensing estimated from vegetation indices (VI) or biophysical variables [22,23]. Multiple studies have confirmed the shift in phenological timing at a regional and global scale due to a shift in climatic conditions, such as changes in precipitation, temperature patterns, and a shift in snowfall timings [4,7]. Using satellite data, the phenological study at a global scale has confirmed a significant advancement in the SOS by 0.38 days per year, a delay in the EOS by 0.45 days per year, and a global increase in the LOS by 0.8 days per year [24]. Similarly, several studies have also reported a shifting phenological period at the regional and continental levels [10,22]. However, the practical application of satellite-based remote sensing in phenological monitoring faces several constraints, including low temporal and spatial resolution, susceptibility to cloud cover, and the modifiable area unit problem (MAUP), where the pixel being monitored may not correspond precisely to the ground location at different times [25–27]. Additionally, while comparing ground observations and satellite-based monitoring, the major difference is the footprint mismatch. Ground observations record phenology at the individual species level, which makes it difficult to compare it with a satellite-based phenological product at the regional scale. This pronounced disparity in footprint size underscores the need for near-surface monitoring techniques that are capable of capturing phenological data at the plot level.

It is interesting to note that the first fully digital camera came into existence after a decade of the first operational earth observation satellite. In recent years, satellite-based monitoring techniques have been complemented by near-surface remote sensing methods, such as time-lapse digital cameras (PhenoCam) [28], in situ measurements taken with radiometric instruments [29], monitoring based on eddy covariance (EC) data [30], and images captured by unmanned aerial vehicles (UAV—temporal resolution depends on the frequency of the flight) [31]. These near-surface remote sensing techniques offer high temporal resolution and better spatial coverage compared to direct ground observations. They provide valuable data that can be used to develop, calibrate, and evaluate satellite-based phenological models and products. Among these four near-surface phenology monitoring techniques, PhenoCam networks have garnered significant attention in the global research community due to their simplicity in data processing and the automated continuous data acquisition capacity at high spatial and temporal (timings pre-programmed) resolutions.

3. PhenoCam as a Promising Technology for Long-Term and Continuous Phenological Monitoring

The PhenoCam system tracks vegetation phenology at a high spatial and temporal resolution using images from digital cameras mounted on a tall tower [32] or small towers situated at a vantage point. This innovative technique allows for the monitoring of vegetation phenology at both individual and local area levels with minimal atmospheric errors. Researchers can analyze the captured images to identify data patterns or anomalies, facilitating a deeper understanding of the vegetation dynamics [33] (Figure 2).

The PhenoCam system captures images in red, green, and blue (RGB) and, optionally, in infrared (IR) bands. Since these images are captured under open atmospheric conditions, fluctuations in brightness due to cloud cover and the time of day can influence the quality of data. However, these effects can be mitigated by calibrating the images using a reference panel kept in the field of view [34]. Data generated from PhenoCam imagery have been utilized for various purposes, such as to assess satellite phenological products [35–37]; to define and validate new phenological models [38]; to better understand the interactions between canopy phenology and the dynamics of ecosystems [39]; and to study the seasonal changes in leaf-level physiological processes that are connected to variations in leaf color [40,41].

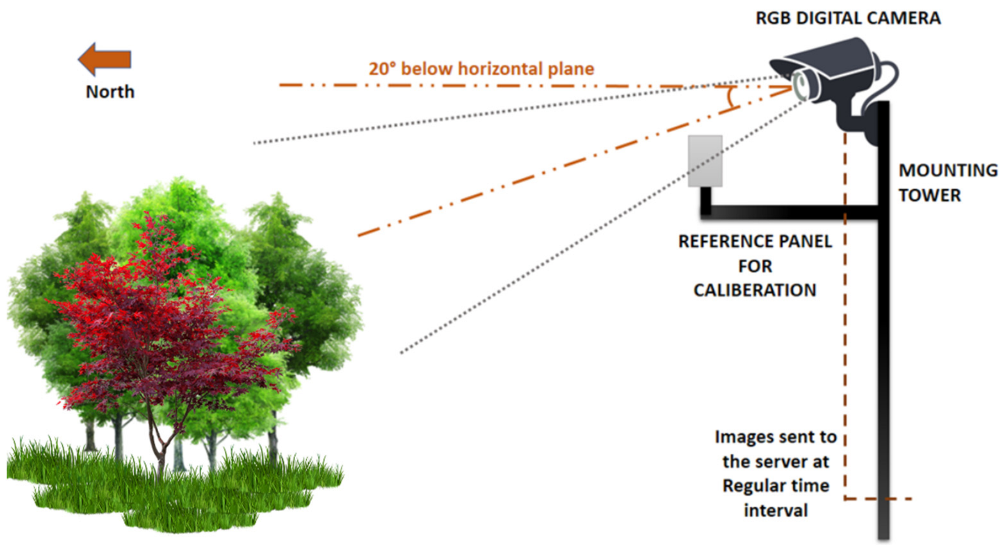

Figure 2. A representation of different components of the PhenoCam system.

In this review, we systematically compared observations from PhenoCam to satellite-based phenological products, the eddy covariance tower, and the ground observation of different ecosystems for which data are available in the literature. The comparison between PhenoCam and various other methods in terms of their performance, as reported in the existing literature, is depicted in Figure 3. The figure presents the correlation coefficients (*r* values) collected from relevant studies, providing a visual representation of the comparative performance of these methods for phenological monitoring. All the literature on global PhenoCam work referenced in this review is included in Table S1.

First, we compared PhenoCam-derived time series green chromatic coordinates (GCC) with MODIS and VIIRS satellite time series data (NDVI) (low-resolution satellites) (Figure 3a). In deciduous forests, the average correlation was found to be 0.87, while in grasslands, it was 0.85 (n = 12). The evergreen forest showed the lowest correlation with a value of 0.7 (n = 7). We also examined the correlation with moderate-resolution satellites such as Landsat and Sentinel. In grasslands, PhenoCam data demonstrated an average correlation of 0.91 (n = 9), while in deciduous forests, it was approximately 0.87 (n = 4). Furthermore (Figure 3b), we evaluated the correlation between extracting SOS and EOS from MODIS data and PhenoCam observations (n = 12). In the deciduous forest, the average correlation for SOS was 0.89, and for EOS, it was 0.81. In grasslands, the correlation between MODIS and PhenoCam for SOS was 0.94, while for EOS, it was 0.70. These studies show that Deciduous forests and Grasslands exhibit a stronger correlation with satellite data, primarily because they vividly display phenological stages. By contrast, Evergreen forests show a relatively lower correlation, which is mainly attributed to the absence of distinct phenological stages and the limitations in temporal resolution provided by satellite data.

Next, we compared PhenoCam time series GCC with gross primary productivity (GPP)-based phenological monitoring using the eddy covariance tower across different ecosystems (Figure 3c). Among the ecosystems studied, grasslands exhibited the highest correlation, with an average R-value of 0.91 (n = 8), followed by deciduous forests with an average R-value of 0.87 (n = 11), and evergreen forests with an R-value of 0.84 (n = 5). Lastly, we compared ground observation data with PhenoCam-derived GCC for various phenological metrics. In the deciduous forest, the correlation for budburst was found to be 0.96 (n = 4); for the leaf area index (LAI), it was 0.93 (n = 2); for the chlorophyll concentration, it was 0.95; and for leaf fall, it was 0.96 (n = 2) (Figure 3d).

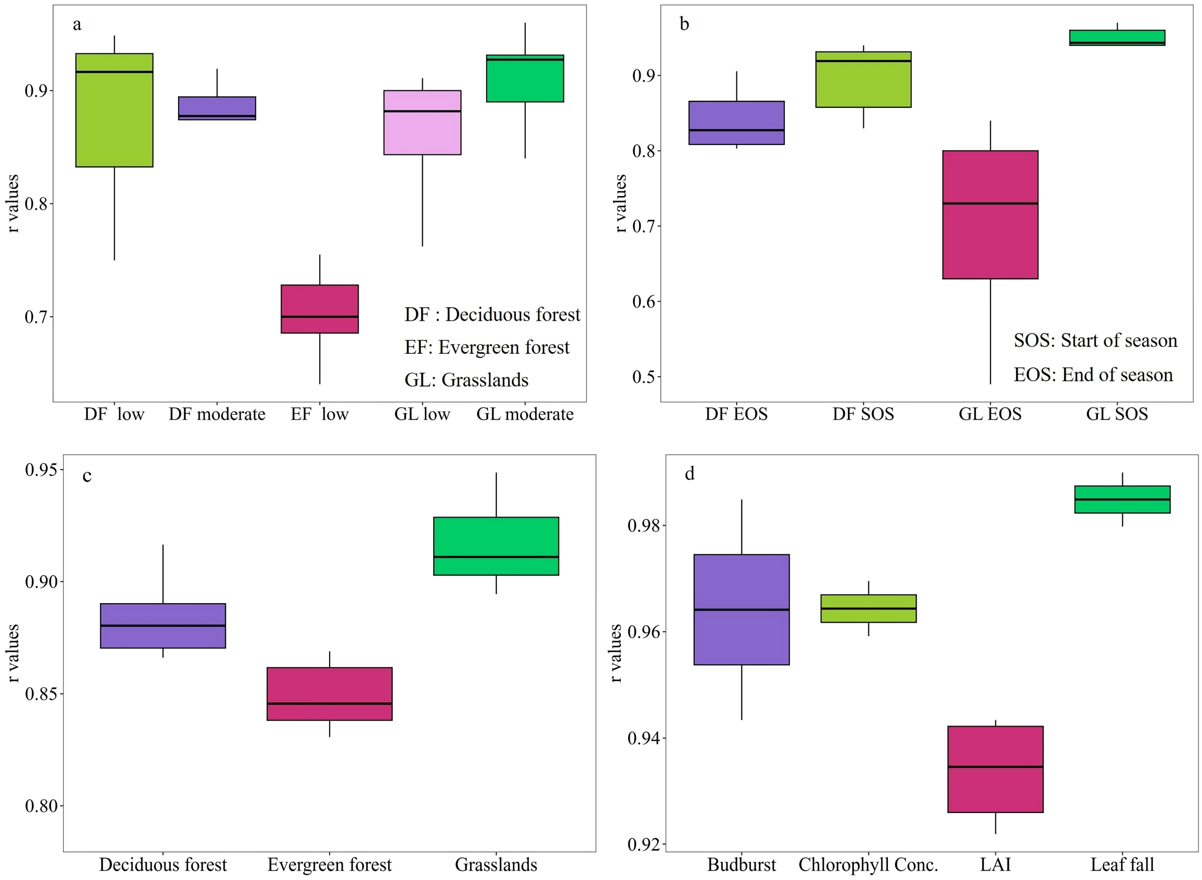

Figure 3. Correlation between PhenoCam data with other phenological monitoring methods, (**a**) PhenoCam to satellite-based NDVI, (**b**) PhenoCam-derived SOS and EOS to MODIS SOS and EOS, (**c**) PhenoCam GCC to eddy covariance gross primary productivity data and (**d**) PhenoCam to ground observations.

Traditionally, the observation of flowering and fruiting phenophases relied on labor-intensive direct ground observations. However, the introduction of the PhenoCam network has revolutionized this process, allowing for the more detailed monitoring of these phenophases. For instance, Chandra et al. (2022) utilized the PhenoCam network to monitor different stages of flowering (budding, initiation, and maturation) and fruiting (fruit development and maturation) phenology in *Rhododendron arboreum* Sm., located in the Himalayas. Their findings reveal a strong correlation between these phenophases and winter soil temperature [42]. Additionally, Mann et al. (2022) developed an automated method using time-lapse cameras to accurately extract flowering phenology (onset, peak, and end of flowering) for two Arctic species, achieving a high accuracy rate of over 90 percent compared to ground observation [43]. Also, Delpierre et al. (2020) reported a strong correlation (r = 0.98) between the within-population variability of budburst (WPVbb) calculated using PhenoCam data and ground observations. This supports the reliability of PhenoCam-derived metrics in capturing fine-scale phenological variations [44]. In addition to this, Kurc & Benton et al. (2010) employed linear regression analysis to demonstrate that greenness (GCC) is closely associated with soil moisture at depths ranging from 0.30 m to 1 m, which corresponds to the densest distribution of creosote bush roots [45]. This finding reinforces the link between PhenoCam-derived observations and ecological factors. Moreover, in the context of evergreen forests, where the correlation between PhenoCam-based observations compared to satellite phenological products tends to be low, Liu et al. (2020) discovered that red chromatic coordinates (RCC) offer a more precise prediction of GPP-based SOS and EOS [46]. This indicates the potential for an improved phenological assessment in evergreen forest ecosystems through the use of RCC data. These studies highlight the potential of PhenoCam data, in combination with satellite data, to accurately monitor phenological changes and bridge the gap between satellite observations and real-world ecological dynamics.

However, RCC, GCC, and NDVI may not reveal the same timings of SOS or EOS as the physical processes associated with these indices are different. RCC and GCC reveal normalized energy from the red and green band from the PhenoCam RGB images, and they reveal that chlorophyll absorbed and reflected energy, hence revealing more about the chlorophyll pigment content in plants. On the other hand, NDVI uses red and NIR bands, and hence, it reveals more about the biomass as well as the health of the plant. During the senescence, the NIR value depends more on fiber content (intercellular arrangements of cells and pigment concentration, respectively), and the red reflection increases due to the absence of chlorophyll absorption and, hence, the magnitude of the NDVI value becomes low as the difference between NIR and RED is diminished [41,46]. Due to these reasons, RCC and GCC may show an early SOS, but NDVI may show a delayed SOS. Additionally, NDVI and other satellite-derived indices are influenced more by the soil background, atmospheric conditions, topography, etc., while GCC and RCC are relatively free (or negligible) from these influences. GCC and RCC could better demarcate leaf phenology, including SOS/EOS stages, while NDVI and other indices represent more plant growth and vigor with a better correlation of photosynthetic variables such as FAPAR/PAR [47,48]. This justifies the use of PhenoCam images for (leaf) phenological studies.

The comparison of ground-based observations with PhenoCam data consistently demonstrates a strong correlation (90%) across various ecosystems. The versatility of PhenoCam technology allows for the focused monitoring of specific species or multiple species, enabling the visual identification of various stages of plant life cycles, such as leafing (leaf buds, mature leaves, abscission of leaves), flowering (flower buds, anthesis of flowers, abscission of flowers), and fruiting (fruit buds, maturation of fruits, abscission of fruits). This review highlights the potential of PhenoCam as a promising alternative to labor-intensive ground observations. By utilizing PhenoCam cameras, researchers and environmentalists can streamline their data collection processes and contribute to a more comprehensive understanding of ecosystem dynamics. PhenoCam cameras, by replacing labor-intensive ground observation methods, represent a valuable tool for advancing ecological research and conservation efforts in poorer countries in the tropics.

4. Global Distribution of PhenoCams

PhenoCam is a viable alternative to the present method of ecosystem phenological monitoring that combines ground-based data with satellite observations [49]. Time-lapse and fixed digital cameras have demonstrated remarkable potential at capturing phenological metrics across a diverse range of biomes. These include high Arctic vegetation [50], North American grasslands [51], Amazon rainforests [52], grasslands in Japan [53], Australian grasslands [33], deciduous and evergreen forests of North America [54], tropical forests of Malaysia [55], and croplands [56]. In this review, we looked at only peer-reviewed articles that had the word "PhenoCam" in their titles or keywords. We carefully read each article and collected important information from them (see Table S1). From this list of 72 studies, we observed that a significant proportion of studies using PhenoCam were conducted in deciduous forests (31.5%), followed by grasslands (19.8%), evergreen forests (17.1%), and shrublands (8.1%) (Figure 4). This diverse distribution of research sites highlights the versatility and broad applicability of PhenoCam in different ecosystem types.

The recognition of the significance of PhenoCam systems in monitoring plant phenology has led to the establishment of several phenological networks worldwide. These networks include the PhenoCam Network—USA [32]—the Phenological Eyes Network—Japan [57]—the National Ecological Observatory Network—USA [58]—the EURO-Pheno Network—Europe [59]—the European Integrated Carbon Observation System (ICOS) Network—Europe [59]—and the Australian PhenoCam Network—Australia [60] (Table S2). When considering the spatial distribution of PhenoCam studies, it is notable that 53 percent of the studies were from North America, followed by 28 percent from Europe and 11 percent from East Asia. This highlights a significant gap in PhenoCam-based monitoring in regions such as Africa, South America, South Asia, Central Asia, and Australia. There is a need to expand the PhenoCam network in these geographies to better understand their global forest dynamics and the impact of global change on forest ecosystems [61].

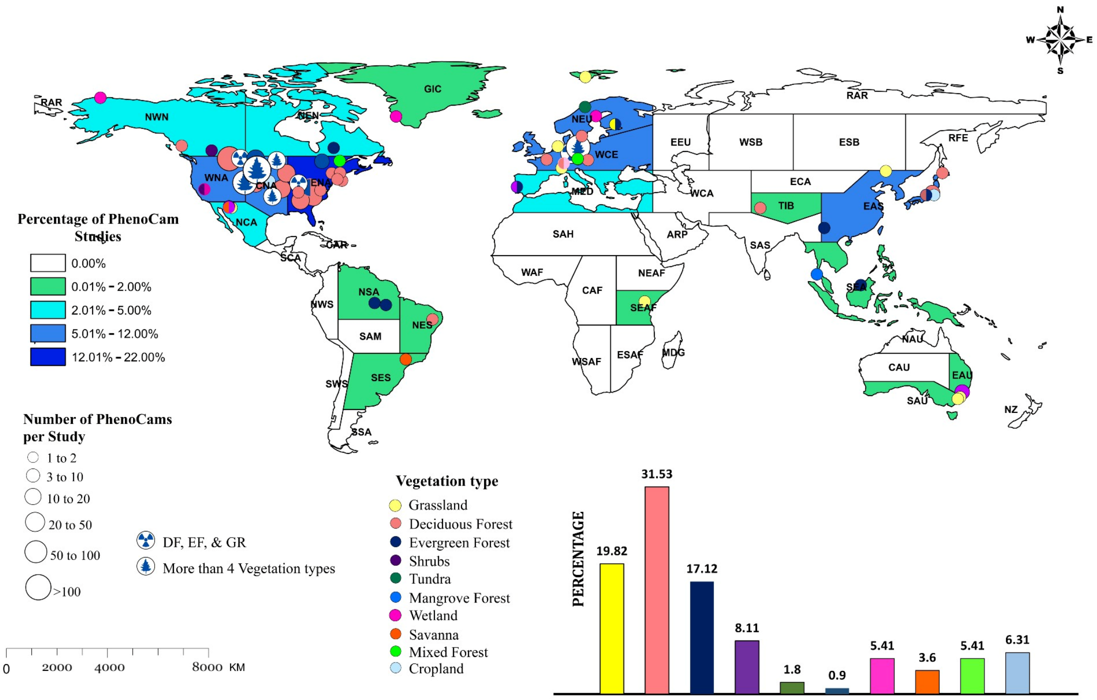

Figure 4. Distribution of published PhenoCam-based studies as per IPCC AR6 regions.

Here, we spotlight India as a case study and discuss the need for a PhenoCam network in India and its potential role in improving forest management in this country. The experiences from the Indian PhenoCam network could be useful in the expansion of PhenoCam networks in geographies with similar socio-economic circumstances, such as the other countries of South Asia, Africa, etc. By expanding the reach of PhenoCam networks to currently underrepresented regions, we can enhance the comprehensive monitoring of vegetation phenology worldwide. This could enable a more holistic perspective on the impact of climate change and contribute to a deeper understanding of ecological processes on a global scale.

5. The State of Phenological Monitoring in India

India is a country that has enormous diversity and endemism of plant species, with a total forest cover of 713,789 sq. km, which is about 21.71% of its total geographical area [62]. According to Champion and Seth, Indian forests have been classified into 16 different forest types and 255 sub-forest types [63]. Each of these forest and sub-forest types exhibits a distinct phenological behavior, necessitating enhanced phenological monitoring in Indian forests. Currently, forest phenological monitoring in India is mainly carried out using traditional ground observations and satellite remote-sensing techniques [20,64,65]. Ground-based phenological studies mainly focused on deciduous forests (tropical moist deciduous forests and tropical dry deciduous forests) and evergreen forests (tropical wet evergreen forests) [66–69] and a few on tropical and subtropical moist forests in the north-east of India [70–72] (Figure 5). The first-ever formal (from the available literature) phenological study in India was conducted from 15 April 1975 to 20 December 1976 and from 14 February 1978 to 15 September 1979 in the dry deciduous forests of Bandipur [64].

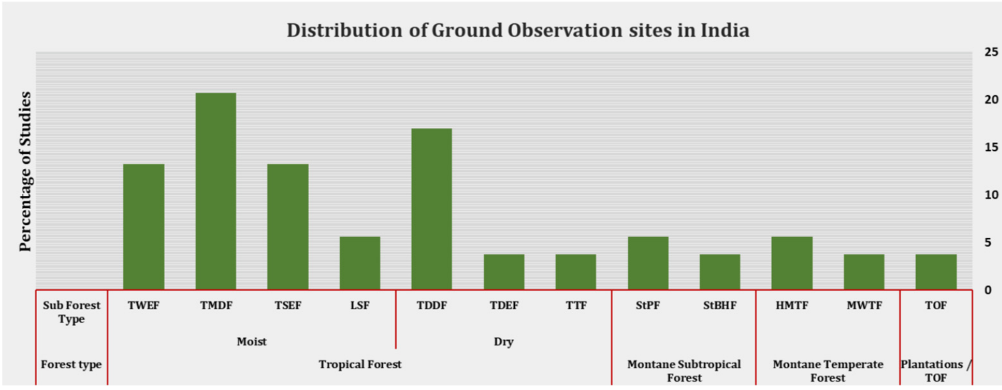

Figure 5. The distribution of ground phenology monitoring sites in India from published journals since 1975.

However, only a few studies have been published for phenological observations over a long period (more than five years), such as the study by Datta & Rane at Pakke Wildlife Sanctuary and Tiger Reserve, Arunachal Pradesh, which lasted six years from 1997 to 1999 and 2009 to 2011, and the study by Suresh & Sukumar at Mudumalai Dry Forests, Tamil Nadu, which lasted from 2000 to 2008 [73,74].

Even though India has 37 (Figure 6, Table S3) distinct ground-based phenology observation sites, it has been reported that there are only six long-term forest phenology monitoring sites in India (most of them are ongoing, and only a few are published): Mudumalai-Tamil Nadu (30 years), Pakke Tiger Reserve-Arunachal Pradesh (1997–2000 and 2009–ongoing), dry forest in Rishi Valley-Andhra Pradesh (10 years), Kalakkad Mundanthurai Tiger Reserve-Tamil Nadu (20+ years), Anamalai Hills-Tamil Nadu (4 years) and dry tropical forest in Nigdale-Maharashtra (7 years) [75]. In addition, India has a long-term, large-scale citizen science initiative for plant monitoring called SeasonWatch. Hitherto, SeasonWatch (https://www.seasonwatch.in/, accessed on 15 October 2023) has registered over 24,617 plants and collected over 6.6 lakh observations on the phenology of these trees.

In addition to this, several satellite-based phenological monitoring studies have been conducted since 1980 [76–78]. However, nationwide ground validation is not possible for satellite-based phenological products due to a lack of ground observations. The published literature provides information for ground validation in a few locations; however, it is difficult to identify the exact date of the year (DOY) from these linguistic distributions (such as early spring, the end of the dry period, and the post or pre-monsoon period). In addition, most of the ground-based phenological studies in India have monitored the major nine phenological stages in the cycle, such as leaves (bud stage, mature, abscission), flowers (bud stage, anthesis, abscission), and fruit (bud stage, maturation, and abscission). However, it is impossible to monitor all these nine phenological stages with a high level of accuracy using satellite data, which is one of the significant limitations of satellite remote sensing in phenology monitoring.

Scientists have employed near-surface digital cameras to circumvent these impediments for phenological monitoring. Sharma et al. (2021) installed a camera in the Western Himalayas to track Betula, utilize phenological temporal trends, and record snow cover patterns [79]. They effectively tracked the phases of greenup, leaf maturity, senescence, and dormancy and reported that greenup occurred four days earlier in 2018 than in 2017, whereas dormancy occurred one day later. Parihar et al. (2013) used digital cameras to monitor forest phenology in Madhav National Park in Madhya Pradesh and compared their findings to satellite data [80]. However, the use of digital cameras for phenology monitoring in India is limited, with studies often focusing on a restricted range of plant species and short monitoring periods.

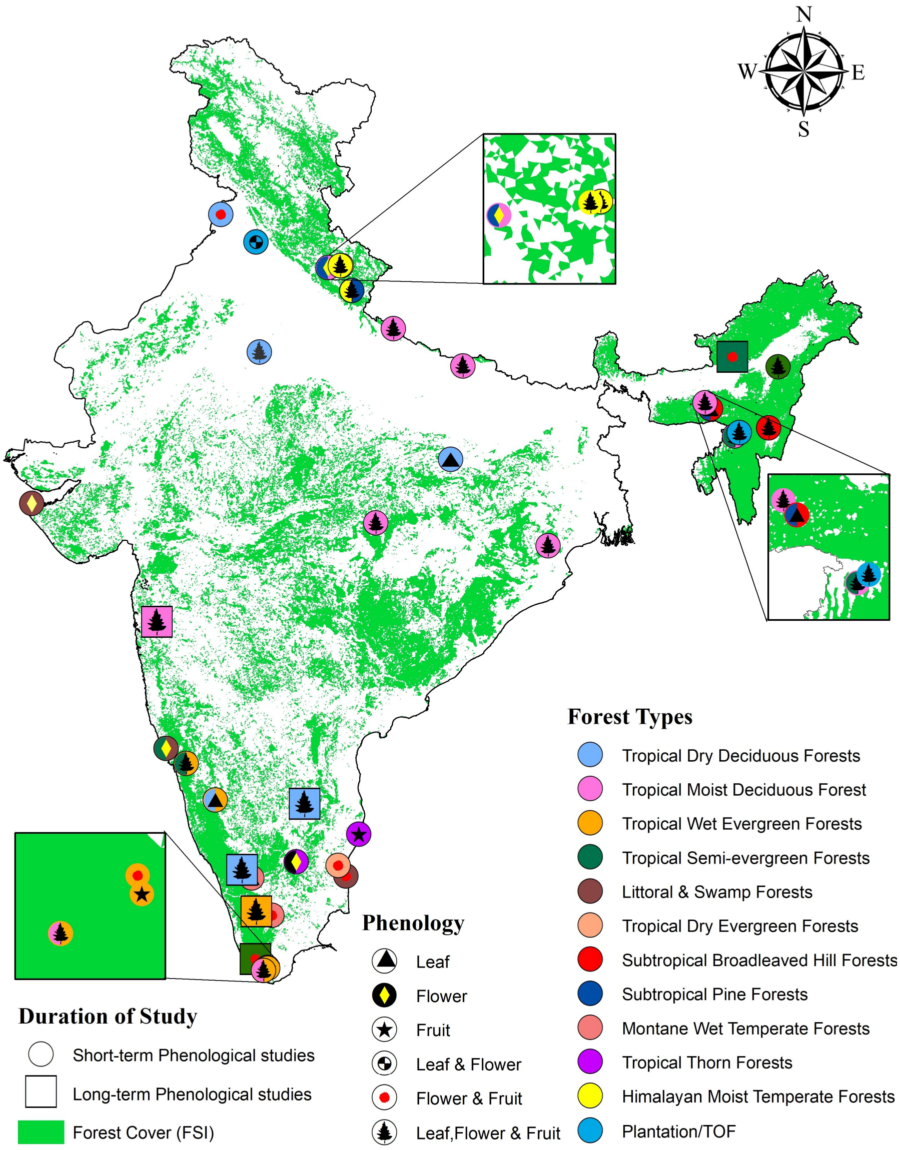

Figure 6. Ground-based forest phenology monitoring sites in India. (Based on the past literature since 1975. We identified 37 ground observation sites as follows: 31 short-term and six long-term).

It is crucial to establish a long-term phenological monitoring network to better understand the drivers and responses to climate change. Short-term studies of 3–5 years (the average period of most financed research projects or a university doctorate thesis) are profoundly inadequate to capture the intrinsic unpredictability of natural systems caused by environmental stochasticity, as evidenced by numerous recent studies conducted worldwide. Indeed, the results of such short-term research can be quite deceiving. Given the absence of a comprehensive long-term ground-based phenological monitoring system across India's diverse forest types and the limitations of satellite-based monitoring, there is a pressing need for a new monitoring network. Daily phenological observations using time-lapse digital cameras, such as PhenoCam, offer a solution to address these challenges. This approach provides high temporal and spatial resolutions, allowing for cost-effective, labor-efficient data collection, long-term monitoring, and reliable canopy phenological monitoring. Adopting digital repeat photography techniques can facilitate the establishment of an extensive and reliable phenological monitoring network in India [54,81,82].

6. Role of the PhenoCam Network in Supporting Forest Management in India

Long-term datasets on ecosystem dynamics are crucial for effective forest management and biodiversity conservation. Unfortunately, in the case of India, there is currently a limited number of long-term observation sites, and access to such datasets is restricted [83]. Introducing a PhenoCam network across various forest types in India could be a valuable addition to forest management efforts. PhenoCams are widely used globally to understand and predict changes in vegetation patterns and phenology, which have significant implications for ecosystem health and climate research.

Gross primary productivity is an important indicator of forest health as well as an indicator of climate change [84]. Wang et al. (2020) showed that GPP derived from PhenoCam shows a higher correlation (R^2 varied from 0.80 to 0.87) with GPP derived from an eddy covariance tower with high statistical significance ($p < 0.01$) [25]. Similarly, PhenoCam-based analysis (Excess green index and GCC) on plant health shows a significant relation to the ground-based metrics of stand health, which includes vigor, mortality, foliar disease occurrence, and root disease symptoms at both the plot and tree level [85]. Several studies have also indicated that camera-derived LAI and chlorophyll concentration correlate with ground-based observations [40,86,87]. Similarly, PhenoCam-derived GCC demonstrates a significant correlation with aboveground green biomass (AGB) in grassland ecosystems [53].

PhenoCam data have proven valuable in tracking global climate events. For instance, Cremonese et al. (2017) effectively utilized time series PhenoCam data from grasslands in the Western European Alps to monitor the impact of heat waves [7]. Similarly, Gonçalves et al. (2020) examined the response of forests to an unexplained drought triggered by El Nino in 2015–2016 and observed post-drought fluctuations in leaf demography using multi-year PhenoCam data [88]. In light of the changing climatic conditions, the introduction of PhenoCam in India's forests holds great promise for enhancing our understanding of ecosystem dynamics, facilitating informed decision-making, and supporting proactive conservation strategies.

In addition to direct monitoring, PhenoCam data can be also used to validate satellite-based products, which are highly used for forest management and decision making in the current scenario. Validating satellite-based phenological products is important for understanding variations in seasonal and inter-annual biome responses due to climatic variability [89]. The following are some of the most widely used satellite-based vegetation products to understand forest dynamics: (a) the Normalized Difference Vegetation Index (NDVI), (b) the Enhanced Vegetation Index (EVI), (c) MODIS LAI, and (d) MODIS and AVHHR Fraction of Absorbed Photosynthetic Active Radiation (fPAR). Currently, data from the eddy covariance tower (EC) [87,90], ground-based measurements of LAI, time-lapse digital photographs, and tower radiation sensors (PAR) are being used to calibrate these products. However, in India, the number of active eddy covariance sites is very limited. Therefore, the establishment of the Indian PhenoCam Network could significantly increase the number of calibration points for satellite-based products, addressing the current gap in phenological monitoring in the South Asian region. Additionally, this could help in validating satellite-derived phenological matrices (e.g., MCD12Q2) and proceed one step closer to qualifying phenological matrices with products from satellites to become one of the essential climate variables (ECVs).

Indian forest calendar for management. Presently, available information about the Indian forests is limited to broad and sporadic measurements (monthly observations in field plots). Such data are inadequate for generating spatial maps on phenology, health, biomass, and other essential datasets. The Forest Survey of India (FSI) conducts satellite-based mapping and monitoring, producing a national forest area assessment report every two years. However, it is insufficient to meet the needs of managing Indian forests effectively. To address this limitation and enhance forest management strategies, the establishment of a long-term PhenoCam network across various Indian forests is crucial. By implementing PhenoCams, which provide continuous and accurate data on shifting phenology, health indicators, biomass estimation, and gross primary productivity, researchers can gain a deeper understanding of the ecological impacts of climate change on different species. Moreover, phonologically informed forest management is crucial for arresting increasing forest fire events in Indian forests, which see surface fires starting with the accumulation of litter during EOS (senescence). The predictive modeling of meteorological variables crucial for defining EOS is the need of the hour.

Improvements in the Dynamic Global Vegetation Models (DGVMs) and understanding the impact of climate change on forest ecosystems in India. Vegetative phenology holds significant importance in DGVMs. These models utilize information on plant biogeography and biogeochemical processes to predict ecosystem fluxes and climate fluctuations in the context of global change scenarios [91]. One crucial input for DGVMs is GPP), which is currently estimated using satellite data and still requires validation in the South Asian region. Recent studies have demonstrated the potential to estimate GPP [25] and LAI [86] using PhenoCam data. This indicates that PhenoCam technology can contribute to improving and strengthening satellite-derived GPP data, enhancing the accuracy of DGVM predictions, and making them more applicable to the unique conditions of the South Asian region. By integrating PhenoCam data into DGVMs, researchers can gain a better understanding of the impacts of climate change on forest ecosystems in India and refine management strategies accordingly.

7. Conclusions

Ground-based phenological observations, as well as PhenoCams, are mainly concentrated in developed and temperate regions, leading to a paucity of observations in the global south, especially across tropical forests. The expansion of long-term forest monitoring, especially the monitoring of phenology, is necessary for improving our understanding of the impact of global change on forest ecosystems globally. Ground-based phenological observations are constrained by a number of limitations, including high recurring costs. PhenoCam represents a cost-effective, efficient, and reliable alternative for ground-based phenological observations. We propose setting up a PhenoCam network covering different forest types in India. This network not only helps in filling a crucial data gap in the South Asian region, but it also provides a template for the expansion of the PhenoCam network in similar geographies across the tropics.

The establishment of an Indian PhenoCam network has the potential to support forest management in India. By providing continuous and accurate data on phenology, health indicators, biomass estimation, and gross primary productivity, this network can enhance our understanding of ecosystem dynamics and conservation strategies and enable informed decision making. Through the integration of PhenoCam data with Dynamic Global Vegetation Models, we can improve future predictions at a local level and refine management strategies in response to the impacts of climate change on forest ecosystems. The implementation of PhenoCam technology could be a valuable addition to India's forest management efforts, addressing the limitations of current monitoring approaches and contributing to the sustainable management of forest resources.

The PhenoCam network has already been successfully implemented in other countries, and it has shown promise in improving our understanding of forest ecosystems and their response to climate change. In India, the network could be particularly valuable for monitoring the impact of heatwaves and droughts on ecosystems, which are becoming increasingly common in the country. By providing detailed insights into how forests adapt to these challenges, this network could help us prioritize conservation efforts and ensure the long-term sustainability of India's forests.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs15245642/s1, Table S1: PhenoCam studies world-wide [92–133]. Table S2: PhenoCam networks worldwide. Table S3: Indian Ground based forest phenology monitoring sites [134–164].

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