



# Trends of Forest Phenology Studies in India-Challenges and Opportunity for Satellite Remote Sensing and Near Surface Sensors

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**Abstract:** Phenology, for being pulse of the ecosystem, elucidates the complex relationship between climate and vegetation, serving as a vital indicator of climate change. India, a biodiversity hotspot, has forests classified into 5 major groups, 16 subgroups, and 255 subtypes based on climatic, edaphic, and successional variations, displaying varying phenological traits. Recent advancements in technology have revolutionized our ability to collect valuable data across various spatial and ecological scales. Despite the abundant observational data capturing phenological changes at various scales, remote sensing remains a relatively less explored tool for operational forest phenology monitoring in Indian forest ecosystems. This comprehensive review explores the latent potential of long-term satellite remote sensing data supported with near surface sensor system networks to reveal complex patterns of phenological dynamics within a spectrum of diverse forest types in India. We found that, majority of the research has predominantly focused on field-based observations limited to moist and dry tropical forests, followed by montane temperate and subtropical forests driven by their ecological importance, higher accessibility, and their sensitivity to climate change impacts. Through the utilization of advanced satellite sensors (e.g., MODIS, Landsat, and Sentinel) thorough investigations have successfully examined the dynamics of vegetation in forest phenological studies. Looking ahead, integrated studies with diverse monitoring methods are crucial for upscaling phenological observations robustly. These advances are necessary to precisely quantify the impacts of a changing world on forest phenology.

**Keywords:** Phenology, Forest dynamics, Phenometrics, Remote Sensing, Vegetation patterns

Phenology, as a holistic environmental discipline that integrates biometeorology, ecology, and evolutionary biology (Morellato et al 2016), functions as the pulse of ecosystems, elucidating the intricate relationship between climate and vegetation, acting as a vital indicator of climate change (Rosenzweig et al 2008). Phenology has served as an important diagnostic proxy for a wide variety of areas, such as climate change (Jin et al 2017, Brown et al 2017), food security (Lobell et al 2008, Alemu and Henebry 2017, Gao and Zhang 2021), drought (de Beurs and Henebry 2008, Chang et al 2021), forest fire risk (Chéret and Denux 2011, Bison 2022), frost hazard (Ge et al 2013, Hänninen 2006), landscape dynamics (Jeganathan et al 2014, Dronova and Taddeo 2022), and biogeochemical cycling (Gray et al 2014, Piao et al 2019), as well as input to a number of prognostic models that are frequently used to make predictions in these fields (Ma et al 2022). It is possible to demonstrate the consequences of environmental change independent of ecological observations based on long-term phenological data (Walther et al 2002, Rosenzweig et al 2007, Jiang et al 2014).

Over the past two decades, there has been a notable

growth in the development of multidisciplinary research frameworks for phenology, which incorporate technological advancements and aim to explore the intricate relationships between phenology, ecosystem function, and species across diverse locations and time periods (Cleland et al 2007, Morissette et al 2009, Pau et al 2011). The Intergovernmental Panel on Climate Change (IPCC) has prioritized the collection and analysis of phenological observations to enhance our comprehension of the biological effects of climate change in response to mounting evidence of early spring onsets (Ciais et al 2014). Moreover, phenology plays a role, as an aspect of Biodiversity Conservation particularly in achieving the goals outlined in objectives 13 (Climate action) and 15 (Life on land) of the Sustainable Development Goals (SDGs). It is essential to study patterns and their influencing factors to effectively develop strategies, for both adapting to and mitigating the impacts of climate change (Radeloff et al 2019).

The recent resurgence of phenology as an ecological specialization is driven by climate change implications, highlighting phenological variations as sensitive indicators of global warming's biological impact (Walther et al 2002).

Changes in vegetation attributes, coupled with the intricate connections to climate change, remain crucial, lacking a comprehensive mechanistic understanding (Richardson et al 2012). Technological advancements, particularly in remote sensing, have expanded phenological observation beyond manual methods, enabling efficient collection of substantial monitoring data from both ground-based and remote sensing technologies (Zhang et al 2003, Zhang et al 2016).

The study of vegetation phenology can provide an imperative knowledge about previous, present, and probable future ecosystem conditions (Wolkovich et al 2014). Alterations in the timing of phenological phenomena could desynchronize species interactions because different species respond to climate change differently (Thackeray et al 2016). The progression of vernal phenomena, the extension of the vegetative period, and the temporal displacement of the conclusion of the growing season (onset of senescence) are just a few of the important indicators of phenological response to the ongoing climate change which are responsible for change in carbon budget. This highlights the interest at the regional and global scales in understanding how climate influences forest ecosystems, with Indian forests serving as a notable case (Chaturvedi et al 2011, White et al 2014, Kumar et al 2019).

In the global context, Indian forests hold exceptional importance as mega-biodiversity hotspots and ecologically significant regions. Indian region and its environs is internationally recognized as one of the mega-diverse countries, harboring approximately 7-8% of the world's recorded species and encompassing four of the biodiversity hotspots identified globally: the Himalaya, Indo-Burma, Western Ghats and Sri Lanka, and Sunda land (Sivaperuman and Venkataraman 2018). These diverse ecosystems represent unique reservoirs of biodiversity and play a vital role in sustaining ecological processes and supporting numerous endemic species. Understanding the phenology of Indian forests becomes imperative in this broader global perspective of biodiversity conservation and sustainable ecosystem management.

### **Brief Historical Overview**

#### **In-situ observation**

The commencement of efforts to observe the phenology of the tree species in India is believed to have taken place in the 1950s. Prior to that, India had undertaken several investigations pertaining to agricultural harvest, agro ecology of the flora (Misra 1946), classification of forests (Champion 1936), and silviculture (Chatterjee 1939). However, no explicit research has been documented on the phenology of forests. The eighth general conference of the United Nations Educational, Scientific, and Cultural Organization

(UNESCO) convened in Montevideo in 1954. The conference aimed to promote global or regional initiatives on scientific matters, specifically those related to the humid tropical zone. The committee was established with the objective of examining issues related to research in the fundamental aspects of the natural sciences that are relevant to the humid tropical zones. The aim was to encourage and support the continuation of such research, and to take the necessary steps to initiate or promote research in those areas where significant problems were not adequately addressed. The symposium featured the participation of several Indian authors who presented their research on the humid tropics of India (Puri 1958).

The deep link between phenology and different aspects of our environment explains why, despite observing phenological events for thousands of years, it was officially acknowledged as a scientific discipline only in the 1900s (Fig. 1). Recognizing the vital role of phenology in various facets of our environment underscores its importance in understanding how our ecosystems work and managing resources, especially with changes in climate and habitats. The majority of phenology related studies in India are based on the field observations carried out during (1 to 3 years' timeframe), with a few longer-term studies (Datta and Rane 2013, Suresh and Sukumar 2018). Figure 1 depicts India's phenological study chronology. These community-level investigations provide a baseline understanding of plant behavior and how it responds to ecological conditions (Haq et al 2021). The limited period of temporal phenology variations hinders comprehending their causes and effects difficult. Few studies quantitatively relate these patterns to climate factors, whereas the majority describe the seasonal rhythms of leaf flushing, flowering, and fruiting. Earlier studies estimated phenophases time and extent by counting species in leaf, flower, or fruit (Kumar and Shahabuddin 2005).

Shukla and Ramakrishnan (1982) conducted the first formal phenological study in Meghalaya, in the northeastern region of India. The majority of phenological research have come from South (Prasad and Hegde 1986, Bhat 1992, Murali and Sukumar 1993, Sundarapandian et al 2005, Nanda et al 2011, Prabakaran et al 2013, Nanda et al 2015, Nanda 2017) and North-east India (Shukla and Ramakrishnan 1982, Boojh and Ramakrishnan 1983, Baruah and Ramakrishnan 1989a, Kikim and Yadava 2001, Paul et al 2018, Devi et al 2020) followed by Western (Jadeja and Nakar 2010), Northern (Ralhan et al 1985, Khare et al 2016), and North-Western India (Kushwaha and Singh 2005), with a few from Central India (Newton 1988) in later years. In India, the phenological research has mainly concentrated on dry deciduous (Prasad and Hegde 1986,

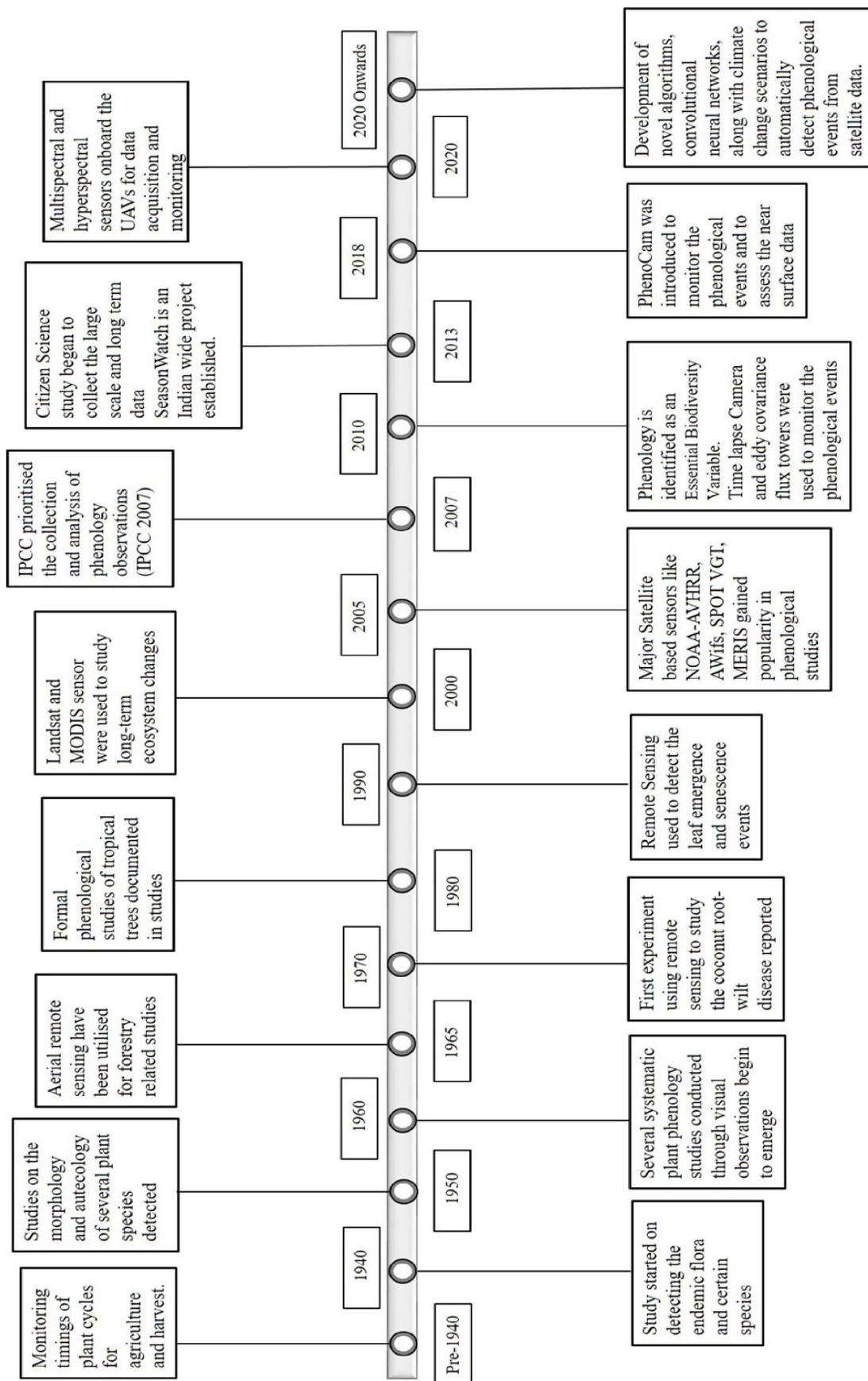


Fig. 1. Timeline of progress of phenological studies in India

Murali and Sukumar 1993, Murali and Sukumar 1994, Kushwaha and Singh 2005, Nanda et al 2011, Nanda et al 2014) and evergreen forests (Krishna et al 2007, Mohandass et al 2016, Nanda 2017) in the south, with less attention paid to tropical (Baruah and Ramakrishnan 1989b, Sundarapandian et al 2005) and subtropical moist forests (Baruah and Ramakrishnan 1989a, Bhat et al 2000, Bhat and Murali 2001) in the northeast (Table 1). This underscores the need for further research and in-depth investigations into the phenological patterns and processes of these tree species to enhance our understanding of their reproductive strategies, ecological interactions, and conservation requirements.

To enhance our understanding of phenology in Indian forests, comprehensive studies encompassing a wide range of tree species are crucial (Kushwaha and Singh 2008). Such investigations yield valuable insights into the temporal patterns of key phenological events, including flowering, fruiting, and leaf emergence. Moreover, they unravel the underlying ecological mechanisms governing these events, shedding light on aspects such as reproductive success, pollination dynamics, seed dispersal mechanisms, and the potential implications of climate change on patterns of phenology. Nevertheless, conducting *in-situ* observations for phenological studies in Indian woods encounters inherent limitations. The vast geographic expanse and diverse forest types pose challenges in achieving representative species and location coverage. Additionally, logistical complexities, time-intensive nature, and associated costs further impede the execution of *in-situ* observations. These constraints accentuate the necessity of complementing *in-situ* data collection with remote sensing techniques and automated phenocam towers, leveraging a more comprehensive phenological observation strategy (Chandra et al 2022). By integrating multiple methodologies and expanding the scope of phenological research in Indian forests, valuable insights into ecological dynamics and conservation imperatives can be gleaned.

Few qualitative studies have been conducted to examine evolutionary concerns associated with ecological determinants of tree phenology (Murali and Sukumar 1993, Murali and Sukumar 1994). With the few exceptions of studies (Krishnan 2002, Joshi and Janarthanam 2004), most of the research conducted focuses on trees. Nautiyal et al (2001) examined the phenology of 171 grass, herb, forb, and shrub species in an alpine pasture at an elevation greater than 3000 m a.m.s.l. Based on the findings, it has been discovered that flowering takes place between May and August after snowmelt, with fruiting occurring between June and August before senescence takes hold before the start of winter. The study conducted by Vashistha et al (2009)

investigated the phenology of a total of 103 species of graminoids, forbs, and shrubs in an alpine pasture situated at an altitude of 3200 m a.m.s.l. in the North-West Himalaya region of India. In their research Joshi and Janarthanam (2004) examined the flowering phenology of a total of 113 endemic species in Goa, encompassing a diverse array of life-forms such as monocots, dicots, herbs, shrubs, trees, and climbers. Moreover, it has been stated that the plateaus located in the northern region of the Western Ghats are distinctive owing to their copiousness of herbaceous native species. The distribution of these endemics is closely linked to precipitation patterns, thus any alteration in the long-term moisture regime would have an impact on their habitat. In a study conducted by Krishnan (2002), the reproductive phenology of sixty understory species, comprising of herbs such as terrestrial shrubs, orchids, and small trees, was examined in a moist evergreen forest located in the southern Western Ghats. Few studies have been carried out on the phenology of specific tree species that are either rare or have significant ecological roles (Ganesh and Davidar 1997, Shankar 2001, Bhat and Kaveriappa 2009, Datta and Rane 2013, Borah and Devi 2014, Nath et al 2016, Upadhaya et al 2018, Devi et al 2020, Chauhan and Chauhan 2020, Nandy et al 2021, Subin et al 2022).

Effective forest management and biodiversity conservation rely on comprehensive long-term datasets on ecosystem dynamics. Unfortunately, in India, there is a limited number of long-term observation sites, and access to such datasets is currently restricted. To comprehensively understand seasonal variations and climatic fluctuations and to detect alterations in the initiation, duration, extent, timing, and synchronization of vegetative and reproductive phases, extensive multi-year investigations are essential. Monitoring changes in species-level biological responses to local climate change can be achieved by utilizing prolonged phenological records derived from plant and animal observation networks. Extended studies in various regions such as Southeast Asia, Australia, Neotropics, Europe/North, America/South, Africa, and America commonly span over 10 - 30 years, occasionally even longer. In an era when the anticipated impacts of climate change are under intense scrutiny, it would be judicious to evaluate the ecological significance and potential advantages of establishing a network of phenological stations.

#### **Satellite Remote Sensing in Phenological Studies**

Remote sensing is recognized as an integral component in the advancement of phenological studies, as it offers substantial potential for comprehending widespread seasonal phenomena over extensive areas (Reed et al 2003). By analyzing long term phenological

**Table 1.** Phenological studies including location, forest types, methods employed, study duration and key findings:

Study region/State	Vegetation type	Reported (With date)		Field or satellite based	Study duration	Reference
		Leaf flushing	Leaf fall			
Meghalaya North-Eastern India	Sub-tropical humid forest	January-March	February-April	Field based	2 years	Shukla and Ramakrishnan (1982)
Meghalaya North-Eastern India	Deciduous Timber Tree	March- early April (From 1 <sup>st</sup> of March at lower altitude and from 20 <sup>th</sup> of March at higher altitude)	February-March	Field based	1 year	Boojh and Ramakrishnan (1983)
Kumaun Himalaya, Uttarakhand North India	Sub-tropical Evergreen	March-April	February-April	Field based	1 year	Ralhan et al (1985)
Bandipur, Karnataka South India	Deciduous Tropical dry deciduous forest	March-April	October-January	Field based	4 years	Prasad and Hegde (1986)
Madhya Pradesh Central India	Moist Deciduous	April - July	December-January	Field based	14 months	Newton (1988)
Shillong, Meghalaya North-East India	Tropical trees	February-March	February-April	Field based	1 year	Baruah and Ramakrishnan 1989a)
Uttar Kannada, Karnataka South India	Tropical moist forest	Early April - May	March-April	Field based	2 years	Bhat (1992)
Mudumalai Sanctuary, Tamil Nadu South India	Tropical Dry Deciduous Forest	January-February	November-January	Field based	2 years	Murali and Sukumar (1993)
Mudumalai, Tamil Nadu Southern India	Tropical Dry Forest	January-March	NA	Field based	2 years	Murali and Sukumar (1994)
Manipur North-east India	Subtropical deciduous and evergreen forest	March-April	November-February	Field based	1 year	Kikim and Yadava (2001)
Western Ghats Tamil Nadu, South India	Tropical moist deciduous forest	February-March	December-January	Field based	2 years	Sundarapandian et al (2005)
Vindhyan Plateau, Sonbhadra Uttar Pradesh North-west India	Tropical dry deciduous forest	March-June	January-March	Field based	2 years	Kushwaha and Singh (2005)
Similipal Biosphere Reserve, Orissa Eastern India	Tropical Moist Deciduous Forest	April	February-April	Field based	1 year	Mishra et al (2006)
Bala Fort Rajasthan Western India	Tropical dry-deciduous thorn forest	February-May	October-December	Field based	3 years	Yadav and Yadav (2008)
Girnar Reserve Forest, Junagadh Gujarat, Western India	Subtropical deciduous forest	February-March	January	Field based	1 year	Jadeja and Nakar (2010)
Bhadra wildlife sanctuary, Karnataka South India	Tropical dry deciduous forest	April-May	January-February	Field based	2 years	Nanda et al (2010)
Katerniaghat wildlife sanctuary, Uttar Pradesh North-west India	Tropical moist deciduous forest	End of March- April	November	Field based	11 months	Bajpai et al (2012)
Uttar Kannada Karnataka South India	Evergreen forest	August	May	Satellite + ground based available data	8 years	Prabakaran et al (2013)
	Semi-evergreen forest	June	February			
	Moist deciduous forest	May	January			

Cont...

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Study region/State	Vegetation type	Reported (With date)		Field or satellite based	Study duration	Reference
		Leaf flushing	Leaf fall			
Hollongapar Gibbon Wildlife Sanctuary, Assam North-east India	Moist Tropical Forest	December and in May (observed twice)	January- February	Field based	2 years	Borah and Devi (2014)
	Tropical dry deciduous forest	Beginning of May –end of May	Mid of January			
Bhadra wildlife sanctuary, Karnataka South India	Tropical evergreen forest	Early January- end of February	Mid of February	Field based	2 years	Nanda et al (2015)
Western Himalayan region of Doon valley, Uttarakhand North India	Moist Deciduous Forest	April	January-March	Satellite based	2 years	Khare et al (2017)
Kemmanugundi, Bhadra wildlife sanctuary Karnataka South India	Tropical evergreen forest	December-early January	August to October	Field based	2 years	Nanda (2017)
Arunachal Pradesh North-east India	Temperate mixed broad-leaved forests	May-June	October-November	Field based	1 year	Paul et al (2018)
Arunachal Pradesh North-east India	Dry mixed deciduous forests	July-October	January-April	Satellite based	33 years	Mohapatra et al (2019)
India	Dry and moist teak forests	July-August	November-end of December	Satellite based	13 years	Ghosh et al (2019)
Nimaichandpur-II, Hailakandi district Assam North-east India	Tropical Deciduous tree- <i>Parkia timoriana</i>	April- May	November-January	Field based	2 years	Devi et al (2020)
Narmada, Gujarat Western India	Tropical dry deciduous forest from 2003-2004	28 July	13 February	Satellite + ground based available data	2 years	Malhi et al (2021)
	Tropical dry deciduous forest from 2013-2014	11 August	22 March			
Rajmahal hills, Jharkhand Eastern India	Deciduous broadleaf forest	March (JD 81)-April (JD 97)	March (JD 65)-March (JD 81)	Satellite based	19 years	Ranjan and Gorai (2022)

data from forests, important issues with climate change modelling and monitoring can be addressed (Prabakaran et al 2013). Observations of phenological occurrences on the ground can give an accurate assessment and can provide a precise understanding of phenological patterns (Nandy et al 2021). However, these conventional field-based methods have several limitations like, huge investment of time and effort to cover a vast region, and it's difficult to make daily observations (required during transition period). Furthermore, these observations face challenges in terms of spatial specificity and are hard to modify. There is also a lack of a substitute to model them for different scenarios or specific conditions. It is at this point that remote sensing emerges with its advantages to address these shortcomings. By utilizing the benefits of stratification, remote sensing mapping and stratification

could cover a vast area with even low intensity sampling. With greater accuracy and precision thanks to the satellites' temporal revisits and long historical records, it is possible to evaluate and analyze altered scenarios. Freely available passive optical satellite imageries with high temporal frequency were widely employed for vegetation phenology study in India (Dash et al 2010, Ghosh et al 2019, Jeganathan et al 2010, Pillai et al 2019, Ayushi et al 2022) and the rest of the world to get over these restrictions (Heumann et al 2007, White et al 2014, Zhang et al 2003, Zheng et al 2022).

#### Role of Spatial and Spectral Resolutions

Accurate assessment of plant phenology's climate change sensitivity requires evaluating year-to-year spatial variations in leaf flush and fall timing over large areas and extended periods. Satellite imagery is optimal for discerning

plant phenology across spatial scales (Czernecki et al 2018, Pastor-Guzman et al 2018, White et al 2009). Spatial and spectral resolutions of satellite sensors are crucial for phenology data quality. High spatial resolution provides detailed local views, while lower resolution offers broader perspectives. Higher spectral resolution enables precise vegetation characterization (Wingate et al 2015).

Commonly used sensors for plant phenology in India include AVHRR (Prasad et al 2008), MERIS MTCI (Jeganathan et al 2010), MODIS (Deka et al 2019), and Landsat (Mohapatra et al 2019). Synchronizing data between sensor families offers advantages like real-time monitoring, increased observation frequency, and more cloud-free observations in evergreen forests (Pastick et al 2018, Li et al 2019). Phenology detection depends on data availability and external factors like cloud cover (Younes et al 2021). The integration of various observation techniques (field, PhenoCam, satellite) at different levels (Species,

landscape, regional) contributes to comprehensive phenological studies.

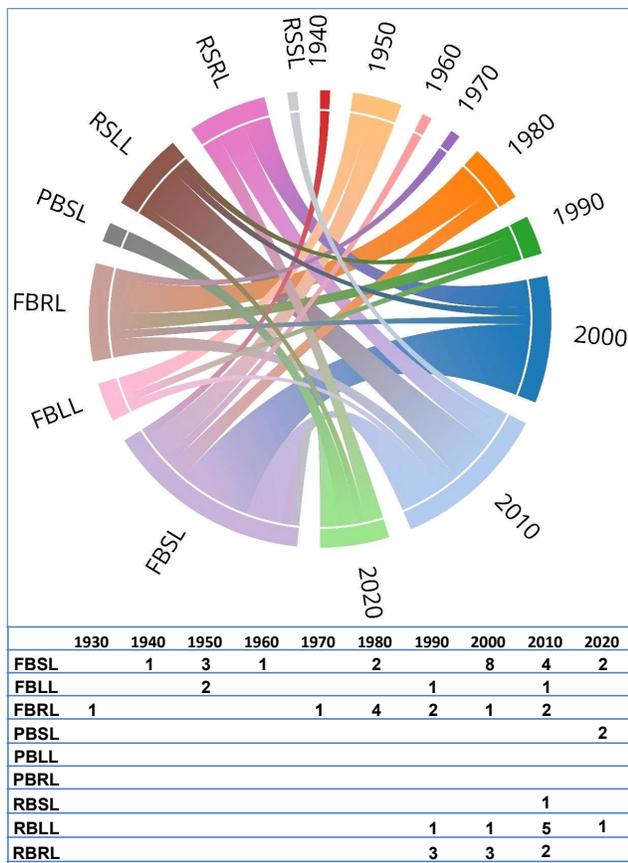
**Long Term Remote Sensing-Based Phenological Studies Combining *In-Situ* and Remote Sensing Data**

Efforts to observe the dynamics of the vegetated land surface from space commenced at the opening of Landsat era (Henebry and de Beurs 2013). Despite Landsat's continuous Earth surface data since 1970, its use for long-term ecosystem studies in India only started in the 2000s, initially limited by cost and processing constraints. The USGS's 2008 open access policy for Landsat data enabled broader time series research on ecology and biodiversity. Vegetation indices derived from remote sensing data contribute significantly to various aspects of forest monitoring, such as forest classification, analysis of vegetation phenology, change detection, and the retrieval of forest biophysical parameters (Glenn et al 2008, Lambert et al 2013).

The widely used normalized difference vegetation index (NDVI) is a key parameter for vegetation studies. A study on moist deciduous forests in the Western Himalaya, using Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) data, assessed phenological changes via NDVI and land surface temperature (LST) (Khare et al 2016). However, limitations in NDVI's ability to fully capture temporal vegetation development led to the introduction of the temporal normalized phenology index (TNPI), offering a valuable alternative to long-term monthly records for understanding forest phenology (Khare et al 2017, Khare and Rossi 2019).

Prasad et al (2008) used NOAA-AVHRR data (1990-2000) to study phenological variations in Indian forests, finding inverse correlations between NDVI and temperature, and positive correlations with precipitation. This aligns with the known influence of these variables on plant phenology, affecting energy, water, and CO2 fluxes (Vadrevu et al 2007). Few studies have used remote sensing to extract phenological variables in India's tropical and subtropical regions (Mohapatra et al 2019). Estimating phenological parameters for these vegetation types via remote sensing will enhance our understanding of their response to climate change.

A continental-scale vegetation map was created using NOAA AVHRR GAC data (1.1 km/4 km resolution), examining NDVI variations due to stress, leaf activity, vegetation amount, and seasonal changes. For finer regional-scale monitoring, the IRS Wide Field Sensor (WiFS) was developed to address NOAA AVHRR limitations (Roy and Joshi 2002). WiFS's temporal NDVI data effectively monitor vegetation cover and phenology (Singh et al 1999),



**Fig. 2.** Number of studies published using different techniques and level of observations

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suitable for tracking short-term vegetation changes regionally (Joshi et al 2006, Joshi et al 2001). With two radiometers, multiple spectral bands, and a wide sweep width, WiFS provides crucial vegetation information at 23.5 m (VNIR) and 70.5 m (SWIR) resolutions. It's valuable for vegetation discrimination, cover mapping, and environmental monitoring, offering sufficient temporal, spatial, and spectral resolutions for regional vegetation dynamics studies.

The low temporal resolution constitutes a significant hindrance to the in-depth examination of dynamic variations, emerging as a notable obstacle in the analysis. However, to overcome these challenges, since the early 2000s, MODIS (Terra and Aqua satellites) and VEGETATION (SPOT satellite) sensors have provided improved multispectral time-series, extending remote sensing applications to phenology and vegetation monitoring over large areas.

While NDVI has been traditionally used for vegetation phenology analysis, recent research focuses on the Enhanced Vegetation Index (EVI), which accounts for background and atmospheric effects and shows increased sensitivity in high biomass areas. Gupta et al (2014) employed MODIS EVI data from 2003 to 2012 to track changes in the phenological transition dates of tropical deciduous broadleaf forests (DBF) in Eastern India. The objective of the study was to examine seasonal and interannual changes in vegetation, with a particular focus on the districts of West Singhbhum and Sundargarh. The results demonstrated that there was an upsurge towards forest degradation: (i) the EVI varied from 0.41 in early April to 0.71 in mid-October; and (ii) the overall pattern declined with a slope of 0.0022. The findings indicate that the end of season (EOS) varied between 1<sup>st</sup> of February and 7<sup>th</sup> March, while the start of season (SOS) varied between 2<sup>nd</sup> of May and 20<sup>th</sup> June. The length of the season decreased overall, peaking in 2007 at 302 days and falling to 235 days in 2010.

Ghosh et al (2019) used MODIS-derived EVI to ascertain that the temporal extent of the growing season in moist teak (*Tectona grandis*) forests have a 48-day longer growing season than dry teak forests, with significant LAI differences (~2.8). The study established a significant correlation between changes in phenology and shifts in rainfall patterns. In their study, Chakraborty et al (2018) examined the spatial patterns of a significant downward trend of forest seasonal greenness over a wide range of forest types in India (2001-2014) using data from an 8-day composite MODIS NDVI time series. Deka et al (2019) utilized a threshold-based approach for phenological parameter extraction, finding stronger NDVI-temperature correlations than NDVI-precipitation. Singh et al (2020a) reported significant NDVI-rainfall

associations, while Deka et al (2019) noted strong NDVI-temperature correlations in humid subtropical regions, suggesting that temperature could be a critical factor in the context of climate change.

Nandy et al (2021) examined the phenological changes of various Sal (*Shorea robusta*) forests in India and investigated the connection between phenology metrics and meteorological variables. Several phenological metrics such as start of season (SOS), length of the season (LOS), maximum of the season (MAX), and end of season (EOS) for teak growing in Narmada forests, Gujarat, India, were calculated using MODIS NDVI time series. Malhi et al (2021) used the derivative method to extract phenology metrics, identifying inflection points in NDVI time series. This method assumes the highest NDVI change rate indicates the start or end of the growing season, extracting key variables like SOS, peak of season (POS), and EOS.

Using a MODIS-EVI dataset, Ranjan and Gorai (2022); monitored phenological trends over the Indian Rajmahal Hills from 2001 to 2019. According to the study's findings, the SOS typically occurred between late, around 22<sup>nd</sup> March (Julian day (JD) 81) up till 7<sup>th</sup> April (JD 97), whereas EOS has primarily been recorded between early 6 March (JD 65) up till 22<sup>nd</sup> March (JD 81). Additionally, between 2001 and 2010, the SOS and EOS of many vegetation types showed a delayed tendency. On the other hand, from 2010 to 2019, the SOS and EOS of every type of plant exhibited an upward trend.

With the use of the SPOT-VGT NDVI time series data product and the TIMESAT tool, Prabhakaran et al (2013); obtained the forest phenological parameters and spatial calendar maps of the Uttar Kannada district, on the west coast of India. They found deciduous forests experience earlier greenness onset than evergreen forests, which have longer grown seasons. Meteorological factors, especially maximum temperature and rainfall, significantly influence forest tree phenology. The majority of satellite sensor-derived phenology studies have used the NDVI calculated from a variety of sensors, including the IRS WiFS (Joshi et al 2006), MODIS (Chakraborty et al 2018;), SPOT-VGT, and the NOAA-AVHRR (Prasad et al 2008). Nevertheless, NDVI has limitations such as saturation at high vegetation biomass and atmospheric influence. The MERIS Terrestrial Chlorophyll Index (MTCI) from the Medium Resolution Imaging Spectrometer (MERIS) sensor offers a potential solution (Dash and Curran 2007). MERIS, with 15 spectral bands and 300 m spatial resolution, making it a promising tool for extracting canopy chlorophyll content data.

The ENVISAT mission's programmable spectrometer MERIS, which operates in the solar reflective spectral band, was utilized to carry out India's first phenology study. The

study captured foliage onset correlating with latitude, with minor inter-annual differences except for 2003 (Dash et al 2010). The study's limitations posed challenges in pinpointing the specific month, week, and date of leaf flushing and leaf fall based on qualitative descriptions (e.g., spring season, early dry period, post-monsoon period). Additionally, it was not possible to link flowering or bud burst data to the MERIS calculations (Atkinson et al 2012).

Jeganathan et al (2010) used the MTCI data, obtained from the Multitemporal MERIS, to investigate the phenology of four significant forest types in India, namely moist deciduous, dry deciduous, evergreen, and semi-evergreen. Their results indicated that the most frequent dates for the onset of greenness (OG) activity for tropical evergreen, semi-evergreen, wet deciduous, and dry deciduous vegetation types were February-April, January-April, March-May, and February-May, respectively. Additionally, the study found that the most frequent dates for end of senescence (ES) activity for tropical evergreen, semi-evergreen, wet deciduous, and dry deciduous vegetation types were February-April, January-April, February-April, and December-April, respectively (Jeganathan et al 2014).

Optical remote sensing faces challenges like atmospheric interference and cloud contamination. Trade-offs exist between spatial, temporal, and spectral resolutions. Various satellites offer different resolutions and revisit times, each with strengths and limitations for phenology studies (Helman 2018, Misra et al 2018). Recent advancements in satellite technology have improved sensing quality, making it crucial for phenology studies. However, challenges persist, including data acquisition costs, lack of ground-based validation, and processing expertise (Zhang et al 2016). There's a scarcity of ground-based observations and PhenoCams in forests, especially in the southern hemisphere (Singh et al 2020b). Efforts are underway in India to understand plant patterns and their connections to phenology and ecosystem models. Integrating PhenoCam data with Dynamic Global Vegetation Models (DGVMs) could improve local-level predictions and management strategies for climate change impacts on forest ecosystems (Jose et al 2023, Wang et al 2020).

### **Objective of Studying Vegetation Phenology**

Three major categories-characterization, explanation, and application-can be used to group together the various research goals for studying vegetation phenology (Caparros Santiago et al 2021). Studies that emphasize spatial or spatiotemporal descriptions of vegetation phenology are included in the characterization process. Numerous researchers have systematically examined the spatial heterogeneity of phenological vegetation dynamics across diverse scales. This exploration often involves the utilization

of mean or median phenometrics derived from satellite data, such as MODIS-NDVI, spanning the study duration (Deka et al 2019, Ayushi et al 2022). Notably, studies conducted in India have revealed that, compared to their evergreen counterparts, deciduous forests show an earlier onset of greenness (Singh et al 2020a). Furthermore, several studies conducted in India have analyzed the year, to year variations specifically focusing on the changes in timing for spring and autumn events (Singh and Sahoo 2019, Negi et al 2022). These investigations utilized sensing data with spatial resolution and have significantly contributed to a deeper understanding of the intricate relationship between vegetation phenology metrics and climatic effects across different types of forests in India. The findings from these studies shed light on the patterns observed in distinct forest ecosystems providing valuable insights into how climatic fluctuations impact vegetation dynamics in the region. This category of research on vegetation phenology also includes investigations into the potential effects of various methodological concerns (Atkinson et al 2012) on phenological estimation, the creation of phenological products (Ganguly et al 2010), or novel techniques that might make it possible to characterize the phenological behavior of vegetation.

The second category of studies includes those whose purpose was to analyze vegetation dynamics and how they relate to environmental conditions (Khare et al 2016, Reddy and Prasad 2018). Numerous investigations looked into the reactions of plant biological cycles to various climate variables. Temperature plays a crucial role in regulating phenological changes, especially in the Dry Deciduous and Temperate zone forests of India, influencing the timing of the growing season onset, duration, and foliage fall (Joshi and Janarthanam 2004). Conversely, water availability and precipitation patterns are key determinants of phenology in tropical forests. Experimental studies linking environmental temperature to plant phenology consistently show that higher temperatures lead to earlier spring and delayed autumn, while lower temperatures result in delayed spring and accelerated autumn. Photoperiod, in conjunction with low temperatures, contributes to deciduous tree leaf fall from November to February. Although some studies explore the relationship between vegetation phenology and variables like the carbon cycle, a significant portion of research in this domain focuses on phenological dynamics and its correlation with various factors (Kale and Roy 2012).

The third category encompasses research utilizing phenometrics as environmental data for diverse applications; the primary objective was not merely to comprehend the phenological behavior of vegetation, but also to explain it.

Most of this research primarily employed phenological data to categorize different types of land cover (Joshi et al 2006). Phenology-based investigations have significantly enhanced the classification of land covers, thereby advancing the comprehension of Earth's surface land cover maps (Qader et al 2016). These studies have proven instrumental in identifying potential changes in land cover, including agricultural expansion (Knauer et al 2017) and deforestation (Valderrama - Landeros et al 2016). This underscores the pivotal role of phenology in monitoring and detecting alterations in land cover, contributing valuable insights to our understanding of the Earth's surface dynamics.

### **Limitations of the Optical Datasets in Long Term Phenology Studies**

The potential for Satellite Remote Sensing to enhance natural resource management is significant, despite certain constraints (Sharma et al 2021). Indian forests, with their rich biodiversity, provide an ideal context for remote sensing-based phenological studies. Recent research has demonstrated the utility of multi-temporal remote sensing data in tracking vegetation phenology relative to climate changes (Zhang et al 2006, Jeganathan et al 2014). Advances in technology have enabled more refined phenology retrieval at higher spatiotemporal resolutions (Ma et al 2022). While precise phenological event detection via satellite data is challenging, broader "land surface phenology (LSP)" descriptors are derived (De Beurs et al 2004, Richardson et al 2013). LSP overcomes limitations of ground-based observations, connecting traditional records with global models (Garonna et al 2018) and offering insights into Indian forest ecosystems (Jeganathan et al 2010). As of now, satellites are the sole practical means of maintaining a constant eye on Earth's dynamics at local to global scales. Specifically, when using optical datasets for long-term phenology studies we encounter some challenges (Berra et al 2019). Both species-specific phenology and vegetation phenology detection using satellite imagery still face a number of obstacles. The main obstacles arise from issues such as pixels, imprecise ground control points, atmospheric distortion and unclear definitions of ground objects (Sharma et al 2022). These factors ultimately affect the accuracy and clarity of the results obtained. These constraints persist across diverse image types, sensors, and platforms, including multi-spectral (hyper-spectral) images, high spatial resolution images, and LiDAR images (Prabakaran et al 2013). Researchers have employed techniques like maximum value compositing (MVC) and masking to address cloud impacts, though these methods have limitations (Dash et al 2010, Atkinson et al 2012, Chakraborty et al 2018).

Ground-based phenological studies in India typically

observe nine plant development stages, which include leaves (Bud stage, mature, abscission), flowers (Bud stage, anthesis, abscission) and fruit (Bud stage, maturation, and abscission), but accurately monitoring all these stages via satellite data remains challenging. Moreover, there is a scarcity of ground-based observations in developing and underdeveloped countries that lack established networks for phenological monitoring. To address this gap, expanding the reach of PhenoCam networks to presently underrepresented regions hold the potential to enhance the comprehensive monitoring of vegetation phenology globally. Such an expansion could offer a more holistic perspective on the ramifications of climate change and contribute to a deeper understanding of ecological processes on a global scale (Jose et al 2023).

### **CONCLUSION**

The review has highlighted several critical areas that warrant further attention to maximize the potential of satellite remote sensing in supporting forest phenological studies in India. The key observations are summarized as follows:

1. The immense potential of satellite remote sensing data to support forest phenological studies is evident, but significant challenges remain that must be addressed.
2. Expanding the spatial scale and improving the spatiotemporal resolution of phenological monitoring is critical for accurately assessing the impacts of environmental changes across diverse forest ecosystems.
3. The limited availability of long-term phenology datasets hinders the understanding of temporal patterns and trends, while the inherent complexity of these ecosystems poses analytical challenges.
4. Integrating in-situ data from local experts with remote sensing analysis is essential to maximize the value and application of satellite data for phenological research.
5. Combining SAR and optical satellite data can provide a more comprehensive dataset to enhance the understanding of woody vegetation dynamics.
6. Exploring alternative vegetation indices beyond the commonly used NDVI and EVI can offer valuable insights into phenological changes.
7. Strengthening interdisciplinary collaboration among remote sensing experts, conservationists, and environmental managers is crucial for shaping a unified research agenda and driving more effective outcomes.
8. Adopting emerging satellite technologies and innovative analytical methods, including machine learning, can advance the mechanistic understanding of phenological processes across multiple scales.

By strategically addressing these key focus areas, the

research community can significantly enhance the accuracy, reliability, and comprehensive application of satellite remote sensing in support of forest phenological studies in India, ultimately driving more impactful and informed decision-making for the sustainable management of these critical ecosystems.

#### ACKNOWLEDGMENTS

The first author is thankful to DST, New Delhi, for the INSPIRE fellowship. The authors are thankful to Shri. N.M. Desai, Director, Space Applications Centre (SAC), ISRO for his constant encouragement and guidance.

#### AUTHOR'S CONTRIBUTIONS

Dhruvi Sedha: Writing-Original Draft preparation, Conceptualization, Methodology, Figure Preparation and Editing. Chandra Prakash Singh: Conceptualization, Formal Analysis, Supervision, Reviewing and Editing. Hitesh Solanki: Supervision. Jincy Rachel Mathew: Visualization and Editing. Mehul R Pandya: Supervision and reviewing. Bimal Bhattacharya: Resources and Supervision. C Jeganathan: Reviewing and Editing. Siddhartha Khare: Reviewing and Editing. All authors have read and agreed to the published version of the manuscript.

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