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Sub-pixel Canopy Phenology reveals divergent Spring transition sequences in Tropical Mixed Deciduous Forest

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Abstract

Vegetation phenology regulates terrestrial carbon uptake and land–atmosphere interactions, and is commonly inferred from satellite-derived vegetation indices such as the Normalised Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). However, these observations represent spatially aggregated signals that mask phenological variability among individual tree canopies in heterogeneous forests. Here, we investigated tree-level spring phenological dynamics in a tropical moist mixed deciduous forest using multispectral PhenoCAM imagery, combining *Optical*(RGB) and *Near-InfraRed*(NIR) indices like *Green Chromatic Coordinate* (Gcc), *Red Chromatic Coordinate* (Rcc), *Normalised Difference Greenness Index* (NDGI), and *Total Brightness* (RGBsum). Three canopy archetypes—a) *Early Leaf Flush*, (b) *Early Flowering-led-Leaf Emergence*, and (c) *Early Defoliation-led-Delayed Green-up* —coexisting within a single satellite pixel, exhibited divergent pheno-phase sequences and timing offsets of several weeks, despite identical environmental forcing. While NDGI consistently captured structural canopy development, Gcc and Rcc reflected plant tissue pigment variation associated with chlorophyll absorption and brown biomass exposure, and RGBsum is strongly influenced by canopy structure and radiative effects. Time-series analysis revealed substantial spectral decoupling across the canopy types indicating asynchronous pheno-transitions due to biological variability and phase-space analysis showed that similar levels of canopy greenness corresponded to distinct structural and optical states across neighbouring canopies, with type-specific nonlinear trajectories and saturation behaviour. Our results demonstrated that spatial aggregation in satellite observations obscures tree-level phenological diversity, potentially biasing estimates of spring onset and ecosystem productivity, indicating the need for multi-metric and scale-aware approaches to phenological characterisation to improve the interpretation of remotely sensed vegetation dynamics in tropical forest ecosystems.

1. Introduction

1.1. Forest phenology as a component of Earth System Processes

Seasonal vegetation phenology regulates the timing and magnitude of land–atmosphere exchanges in terrestrial ecosystems. Concurrently, changes in leaf area and canopy structure alter surface albedo, aerodynamic canopy roughness, and evapotranspiration, thereby modulating carbon uptake, water fluxes, and surface energy balance. The onset and duration of canopy development controls the seasonal activation of photosynthesis, influencing the timing of carbon uptake and the trajectory of gross primary productivity (GPP) and ecosystem carbon balance (Fang et al., 2023; Tang et al., 2016; Xia et al., 2015; Yao et al., 2022).

At broader scales, shifts in growing season timing alter water-use efficiency and energy partitioning, linking phenology directly to climate feedbacks and ecosystem function (Jin et al., 2017; Li et al., 2024; Yang and Noormets, 2021). Recent syntheses demonstrate that phenology jointly controls ecosystem productivity alongside physiological processes, constraining terrestrial carbon dynamics and their sensitivity to climate variability (Li et al., 2024; Norton et al., 2023; Xia et al., 2015). These findings establish phenology as both a biological process and a key parameter in Earth system models.

Because of its broad spatial relevance ,vegetation phenology is commonly inferred from satellite observations using greenness-based indices such as NDVI and EVI, enabling large-scale monitoring of seasonal dynamics (Caparros-Santiago et al., 2021; Gašparović et al., 2024; Zeng et al., 2020). However, these observations represent spatially aggregated signals, raising questions about how underlying biological variability is expressed at the pixel scale.

1.1. Phenological remote sensing approaches and limitations of spatial aggregation

Insights from Satellite-derived phenology are strongly influenced by preprocessing and extraction methods, including smoothing, thresholding, and curve fitting functions, which introduce variability in phenological metrics (Jönsson and Eklundh, 2003; Tan et al., 2011; Zhang et al., 2006). As a result, no consensus exists on optimal approaches across ecosystems (Caparros-Santiago et al., 2021; Zeng et al., 2020).

Beyond methodological issues, vegetation indices exhibit fundamental biophysical limitations. NDVI saturates at moderate to high leaf area index (LAI) and is influenced by non-green components such as woody material and senescent tissues, reducing sensitivity in dense canopies (Gamon et al., 1995; Huang et al., 2021; Nagai et al., 2010). Mixed pixel signature further complicate interpretation, as changes in sub-pixel composition can produce apparent phenological shifts at pixel level, independent of actual biological transitions (Chen et al., 2018).

In heterogeneous forests, these effects are amplified by species diversity and vertical canopy structure, with satellite signals integrating multiple phenological responses into a single trajectory (Ferrara et al., 2023; Fu et al., 2014; Helman, 2018). Empirical evidence shows that satellite-derived phenology may disproportionately reflect dominant or early-flushing species, masking broader community dynamics (Fu et al., 2014).

Environmental and observational constraints introduce additional uncertainties in phenological estimates (Ferrara et al., 2023; Nagai et al., 2010). Collectively, these limitations indicate that satellite-derived phenology represents a spatially aggregated signal that obscures fine-scale variability within complex heterogeneous ecosystems.

1.2. Phenological heterogeneity and scale mismatches

Phenological dynamics are inherently heterogeneous across species and spatial scales. Ground-based observations reveal substantial variability in phenological timing among individual trees, particularly in diverse ecosystems. In tropical forests, asynchronous phenological strategies further increase this variability, producing complex seasonal patterns (Kearsley et al., 2024; Wagner et al., 2013).

Comparisons between satellite and ground observations consistently show discrepancies in phenological timing, often on the order of several weeks (Donnelly et al., 2022; Guzmán Q. et al., 2019; Klosterman et al., 2014). These differences arise because satellite observations capture integrated canopy responses, whereas ground measurements reflect discrete biological events (Donnelly et al., 2022; Dronova and Taddeo, 2022; Guzmán Q. et al., 2019; Klosterman et al., 2014). Landscape heterogeneity further modulates these discrepancies, as variations in species composition and canopy structure influence how fine-scale signals are aggregated into pixel-scale observations (Klosterman et al., 2014).

1.3. Unresolved tree-level variability within satellite pixels

Near-surface observations have revealed substantial intra-canopy variability in phenological dynamics (Morellato et al., 2010). Multi-scale studies show that discrepancies between near-surface and satellite observations increase in heterogeneous environments (Klosterman et al., 2014; Thapa et al., 2021). Prior work has shown that subdividing PhenoCAM imagery into smaller regions of interest can reveal variability in transition timing among individual trees, but such approaches have largely been confined to single-species or structurally simple forests (Delpierre et al., 2020).

High-resolution approaches such as UAV-based monitoring have enabled individual tree phenology analysis, revealing significant variability within mixed-species forests (Kleinsmann et al., 2023). However, these methods face challenges in complex canopies, including crown delineation and signal separation.

Satellite pixels inherently integrate signals from multiple species and canopy layers, producing composite phenological trajectories that obscure underlying biological processes (Chen et al., 2018). Additionally, tropical ecosystems remain underrepresented in phenological monitoring despite their high diversity (Caparros-Santiago et al., 2021; Jose et al., 2023).

1.4. PhenoCAM as an intermediate observational scale

PhenoCAM systems provide high-frequency monitoring of canopy dynamics using RGB-based indices such as GCC and RCC, which show strong agreement with phenological transitions like Bud-burst, Greenup, Senescence, and Dormancy, and other ecosystem functions with close agreement to ground observations in relatively homogeneous forest stands (Keenan et al., 2014; Kumar et al., 2025; Li et al., 2023; Richardson, 2019; Toomey et al., 2015).

These observations reduce atmospheric interference and enable detailed tracking of phenological transitions, making them valuable for validation and scaling of satellite-derived metrics (Thapa et al., 2021; Toomey et al., 2015). However, most analyses aggregate signals across regions of interest, limiting the ability to resolve variability among individual tree canopies (Keenan et al., 2014).

1.5. Spectral indices and multidimensional phenology

Different vegetation indices capture distinct aspects of canopy dynamics. Greenness-based indices track visual canopy development but may exhibit temporal offsets relative to biochemical processes (Yang et al., 2014). Indices incorporating Red and NIR wavelengths provide complementary information on canopy structure, pigment composition, and photosynthetic activity (Liu et al., 2020; Wong et al., 2022; Yang et al., 2022). Comparative studies show divergence among indices during phenological transitions, particularly during rapid change periods such as green-up and senescence [32,40]. These findings indicate that phenology is inherently multidimensional and cannot be fully represented by a single metric.

Existing PhenoCAM studies reveal phase-dependent sensitivity of spectral indices, with higher reliability during spring greenup compared to other transitions (Kumar et al., 2025; Li et al., 2023), suggesting that different phenophases may be differentially expressed across spectral channels. However, current approaches remain largely constrained to image-wide canopy-averaged representations, with limited integration of spatially explicit inter-canopy information required to resolve sub-pixel variability in structurally complex forests(Reyes-González et al., 2021).

1.6. What we did? Sub-pixel, multispectral, tree-resolved phenological analysis

Addressing the above-mentioned gap, we investigated tree-level spring (February-June) phenological transitions within a heterogeneous tropical moist deciduous forest site using multispectral PhenoCAM observations.

Based on the hypothesis that neighbouring canopies belonging to different species of trees sharing the same niche conditions would display asynchronous phenological transition behaviour at the canopy scale, we had decided to resolve individual canopy signals in RGB and NIR images, trying to analyse their differences in pheno-phase sequence and transition timing among neighbouring trees occupying the same satellite pixel.

Three types of individual canopies were selected based on visually detectable differences in phenological behaviour from time-lapse PhenoCAM data of the spring of 2023. These included canopies with early leaf emergence and canopy saturation/closure, early flowering followed by bud burst, as well as transient leafless, dry phases followed by late season leaf flush.

While chromatic coordinates of red and green colour channels were used for their sensitivity towards dry, woody plant materials and green chlorophyll containing parts respectively, red-NIR derived NDGI had served as a better proxy for leaf initiation and canopy sustenance, along-with RGBsum has been derived to mark colour agnostic phenological changes like bright white flowering signals and canopy closure.

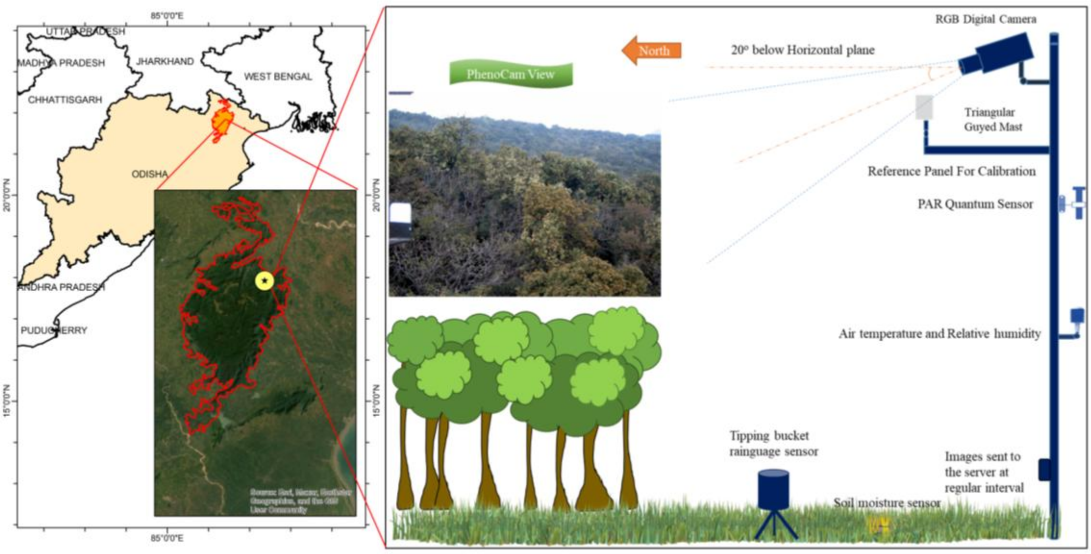

Fig. 2.1(a)- Study area map shows location of Simlipal Biosphere Reserve and PhenoCAM tower (left) and tower setup and camera viewing geometry over surrounding canopy (right)

2. Data and Methods

2.1. Study site and canopy selection

The study was conducted in a tropical mixed moist deciduous forest inside Simlipal Biosphere Reserve in Odisha Fig. 2.1(a) , characterized by strong seasonal leaf dynamics during the pre-monsoon period. The analysis focused on a small set of individual tree crowns observed within the field of view of a fixed ground-based optical camera system. Regions of interest (ROIs) corresponding to distinct tree canopies had been manually delineated using high-resolution imagery to isolate individual crowns that remained spatially stable throughout the observation period.

The selected canopies were chosen based on three criteria:

1. First, the trees had to be co-located within a small spatial extent, ensuring that they experience nearly identical meteorological forcing.

2. Second, the crowns were to be contained within the footprint of a single satellite pixel, enabling direct comparison between canopy-scale and satellite-scale observations.
3. Third, visual inspection of time-lapse imagery revealed distinct seasonal canopy trajectories, including early leaf emergence, delayed leaf flush, and sequences involving transient leafless phases.

These criteria allowed us to isolate differences in phenological behaviour among neighbouring trees while minimising confounding environmental variability.

2.2. Multispectral PhenoCAM observations

Canopy images were obtained using a multispectral PhenoCAM system in the Red(R), Green(G), Blue(B) and NIR spectral bands at a half-hourly temporal resolution which are aggregated to 'daily composite' images using channel wise daily median filters to avoid illumination and exposure effects as well as clouds and fogs. This configuration enabled simultaneous observation of both chromatic canopy properties and structural vegetation signals at daily temporal resolution.

For each selected canopy, a fixed region of interest (ROI) was delineated within the image frame to capture the dominant portion of the target crown, while avoiding contamination from neighbouring canopies, woody biomass and soil background radiation. Time series of mean digital numbers for the RGB and NIR channels were extracted for each ROI. From these band values, chromatic coordinates and IR-based vegetation metrics were calculated to characterize canopy optical properties through time. Duplicates (named A and B) were sampled for each of the canopy type and the average of their values were considered for avoiding sampling errors from single ROI. It was also ensured that samples were spread across the field of view to avoid illumination and capture angle bias.

The PhenoCAM served primarily as an observational lens for resolving individual-tree phenological dynamics that could not be distinguished within spatially aggregated satellite pixels. The high temporal resolution and canopy-level perspective allowed detection of transitions such as leaf emergence, canopy closure, flowering and transient leafless phases within individual crowns.

2.3. Sentinel-2 based Greenness Indices

Standard Greenness Vegetation Indices (VIs) like Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) were used in this study to be used as the background satellite signature which had been measured over an area on the ground covered by a single satellite pixel. The canopy complexity and heterogeneity of phenological cycles over an area of 100 m^2 had been reduced into a single greenness value based on individual band radiances. This data was prepared as 4–8-day aggregates to ensure best possible temporal continuity and least number of radiometric artefacts caused due to haze and clouds. Both NDVI and EVI values were calculated using standard formulae and Sentinel 2 MSI NIR (β_8), Red(β_4) and Blue(β_2) bands which are available in Google Earth Engine.

$$\mathbf{NDVI} = \frac{\beta_8 - \beta_4}{\beta_8 + \beta_4} \ldots\ldots\ldots.(\mathbf{2.3}\boldsymbol{a})$$

$$\boldsymbol{EVI} = 2.5\left[\frac{\beta_8 - \beta_4}{\beta_8 + (6 \times \beta_4) - (7.5 \times \beta_2) + 1}\right] \ldots\ldots\ldots.(\mathbf{2.3}\boldsymbol{b})$$

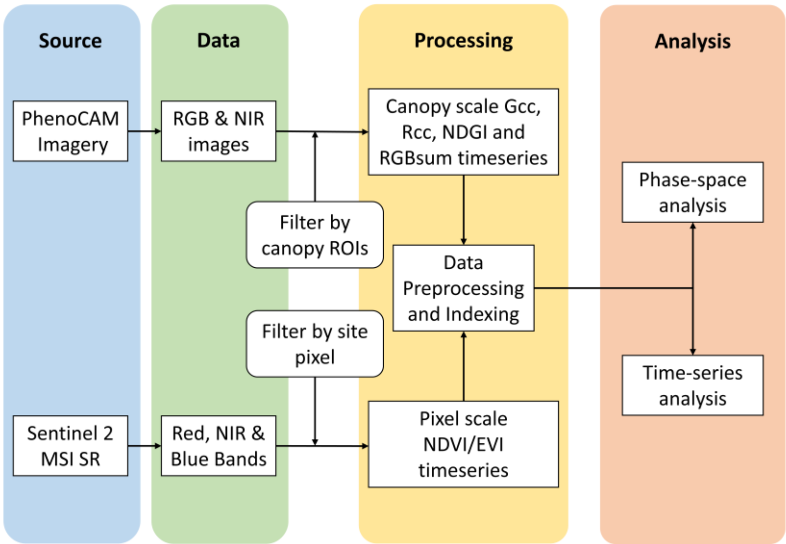

Fig. 2.5(a) Schematic flowchart of extraction, processing and analysis of Satellite and PhenoCAM data

2.4. Phenological metrics calculation for Pheno-transition detection

Phenological dynamics were quantified using spectral metrics derived from the visible and infrared bands. Greenness was characterized using the Gcc, defined as the ratio of green reflectance to total visible reflectance, while woody or non-green dominance was represented by the Rcc. Structural canopy development was captured using total brightness i.e. sum of RGB channels (RGBsum) due to its sensitivity to colour agnostic phenological transitions which increase (e.g. white flowering, leaf flush) or decrease (e.g. tissue drying, canopy saturation, leaf aging) overall canopy reflectance.

An infrared-based vegetation index (NDGI) derived from red and near-infrared bands, which responds to the combined effects of chlorophyll absorption and NIR scattering associated with leaf emergence and canopy expansion. It is important to note that the NIR signal was obtained from a broadband camera response using a mechanical IR filter and does not represent a spectrally discrete or radiometrically calibrated NIR band. Therefore, the index-NDGI is rather interpreted as a relative index of temporal canopy dynamics based on IR reflectance rather than a physically rigorous analogue of standard NDVI or comparable satellite-derived indices.

$$\boldsymbol{R_{cc}} = \frac{R}{R+G+B} \ldots \ldots \ldots (\mathbf{2.4a})$$

$$\boldsymbol{G_{cc}} = \frac{G}{R+G+B} \ldots \ldots \ldots (\mathbf{2.4b})$$

$$\boldsymbol{NDGI} = \frac{NIR-R}{NIR+R} \ldots \ldots \ldots (\mathbf{2.4c})$$

$$\boldsymbol{RGB_{sum}} = R+G+B \ldots \ldots \ldots (\mathbf{2.4d})$$

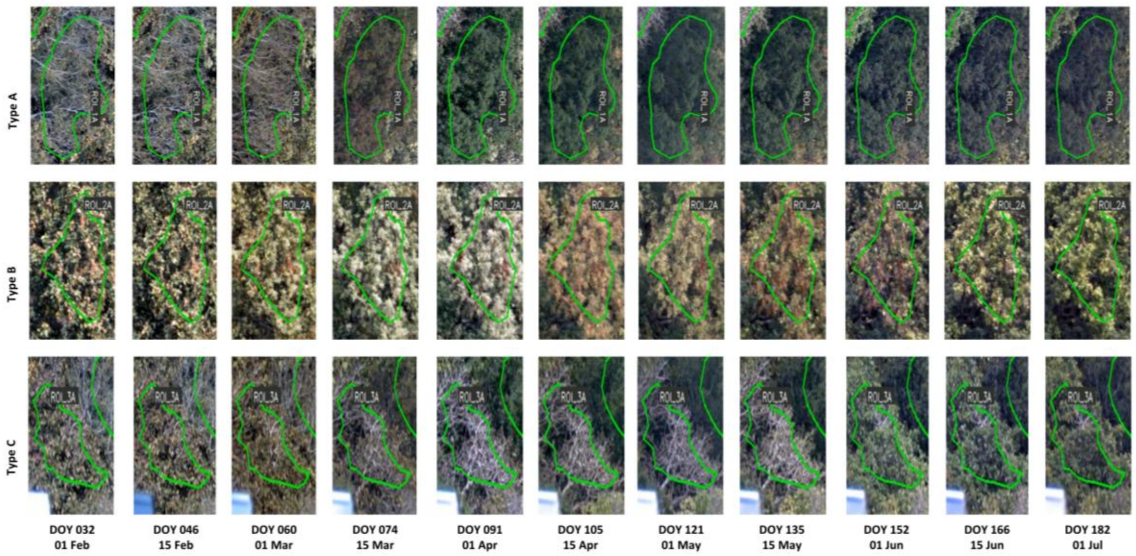

Fig. 3(a) – Row panels showing phenological changes of representative selected canopies (ROIs demarcated with green polygons) over the period of study between 01.02.23 and 01.07.23 sampled at 15 days intervals.

2.5. Pre-processing and harmonization of satellite and PhenoCAM datasets

Owing to the different spatial and temporal resolutions of PhenoCAM and Sentinel-2 datasets along with the differences in geometric and radiometric calibrations, both the datasets were put through rigorous pre-processing and harmonization before further analysis (Fig. 2.5(a)). As mentioned in the previous section, half-hourly PhenoCAM images were reduced to daily median images using ROI-wise daily median of spatially averaged pixel values in each colour channel. This reduced spatial and temporal contamination due to changes in canopy illumination and atmospheric conditions. Pre-processing included gap-filling and denoising of the satellite and PhenoCAM timeseries datasets using kernel-based LOESS and Savitzky-Golay filters. Thereafter the satellite dataset was temporally indexed with the daily PhenoCAM data points using statistical downscaling techniques like cubic spline interpolation.

All spectral parameters, except satellite-derived NDVI and EVI and PhenoCAM-derived NDGI, were normalized between their seasonal minimum and maximum values to emphasize relative temporal dynamics and enable comparison across different variables and canopy types. This intra-seasonal normalization reduces biases arising from background contamination, illumination variability, structural heterogeneity, and viewing geometry. As a result, the analysis focuses on the timing and sequence of relative changes associated with phenological transitions rather than absolute differences in magnitude.

3. Results and Discussions

Observations and insights from PhenoCAM metrics were interpreted alongside frame-by-frame basis visual interpretation of canopy images. Three types of canopies had been identified and sampled in duplicates (A and B) based on distinct phenological transitions over the selected period between 1st February 2023 and 1st July 2023. ROIs were selected based on their stability, visibility and clarity in the image frame while avoiding fluctuations in exposure, illumination bias as well background contamination.

Based on visual interpretation of multi-temporal canopy images, as shown in Fig. 3(a), we classified three types of canopies based on their dominant spring phenological archetypes.

Type A Canopy – [Early Leaf Flush → Canopy Closure → Leaf Maturation] Exhibited early season greenup with rapid canopy closure. Leaf maturation and canopy closure in late season caused darkening of green signature as well as decreased overall brightness.

Type B Canopy – [Early Flowering → Canopy Drying → Leaf Emergence] Exhibited early season bright whitish flowering phase followed by drying and delayed greenup. No significant leaf-off bare canopy phase was visible.

Type C Canopy – [Early Defoliation → Leafless Canopy → Late Greenup] Exhibited early season defoliation, transitioning through a mid-season leafless canopy stage followed by late spring rapid greenup.

Such contrasting pheno-sequences and green-up timings, hinted at distinct radiation and resources use strategies adopted by co-located canopies, consistent with asynchronous phenological in tropical forests reported by previous studies (Kearsley et al., 2024; Wagner et al., 2013). PhenoCAM derived parameters were used subsequently for a deep-dive into such behaviour.

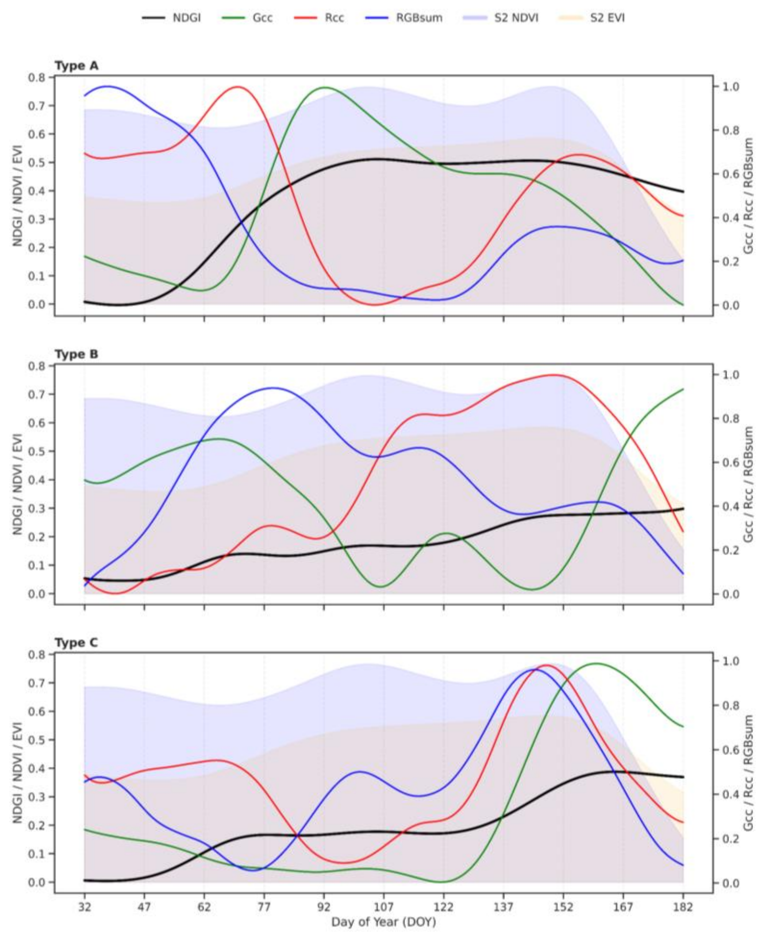

Fig 3(b)- Spring phenological changes as observed with the help of the selected spectral parameters across the three selected canopy types. Shaded curves in the background shows the pixel level Sentinel 2 NDVI and EVI profile which acts as a spatial generalization of all the three canopy types.

3.1. Divergent-asynchronous phenological sequences among neighbouring canopies

Time-series analysis of co-located canopy ROIs (Fig. 3(b)) revealed markedly different spring phenological time-series trajectories among neighbouring tree canopies despite exposure to identical environmental forcing. Similar intra-stand divergence in individual tree responses had been observed by near-surface studies ((Morellato et al., 2010; Richardson et al., 2009) Type A canopy exhibited an early structural development, with NDGI increasing prior to a rapid rise in Gcc and a concurrent decline in Rcc, indicating canopy closure and pigment maturation. Type C canopies followed a delayed development, with an initial decline in greenness and elevated Rcc consistent with defoliation and a transient leafless state, followed by rapid late-season recovery. Type B canopies displayed intermediate and irregular behaviour, with multiple inflection points and transient increases in overall brightness and chromatic signals, suggesting strong early season flowering and tissue drying, and subsequent canopy recovery. These patterns confirmed strong intra-site heterogeneity in phenological development and associated productivity mechanisms of distinct species rather than synchronized transitions (Wagner et al., 2013).

Differences in phenological sequences were accompanied by substantial timing offsets of key transitions. In early-flushing canopies, NDGI increased several weeks before optical greening (Gcc increase and Rcc decline), whereas in late-flushing canopies these transitions occur rapidly and nearly synchronously. Despite these offsets, the internal ordering of transitions within individual canopies remains consistent, with structural emergence preceding or coinciding with optical changes during canopy closure. This indicated that canopy development involved related but decoupled structural and optical processes across the canopy types. Similar temporal offsets between structural and optical signals had been reported, reflecting decoupling between canopy development and biochemical processes (Toomey et al., 2015; Yang et al., 2014)

3.2. Differential sensitivity of structural and optical metrics

Associated spectral indices did not evolve in correlation with greenness, which was broadly captured by Gcc. NDGI, a colour agnostic structural metric, increased gradually and saturated late in the season, while Rcc exhibited strong sensitivity to pigment dynamics, decreasing with chlorophyll absorption and increasing in response to exposed non-green surfaces. RGBsum varied independently, reflecting sensitivity to illumination, canopy openness, and reflective surfaces such as flowers or woody elements. This divergence indicated that optical signals captured distinct components of canopy state including biochemical absorption, structural closure, and radiative transfer effects (Liu et al., 2020; Wong et al., 2022).

3.3. Scale-dependent multi-dimensional phenological decoupling

The asynchronous evolution of spectral variables relative to Gcc demonstrated that phenology was inherently multi-dimensional. Similar levels of canopy greenness corresponded to different spectral configurations at different times, indicating that canopy state could not be uniquely defined by a single spectral or temporal index. Previous studies have reported similar global patterns of scale-dependent asynchrony between different components of ecosystem function, with NDVI, Fluorescense (SIF) and camera based indices (Dronova and Taddeo, 2022; Wang et al., 2020) . Instead, canopy development reflected the interaction of multiple structural, biochemical, and radiative processes.

Individual tree crowns exhibited asynchronous pheno-phase sequences and timings, whereas satellite indices such as NDVI and EVI captured a spatially integrated signal that would smooth these differences. As a result, pixel-scale phenology masked the coexistence of multiple phenological pathways within a single heterogenous patch (Chen et al., 2018; Helman, 2018), obscuring early-season transitions and influencing estimates of spring onset and ecosystem productivity.

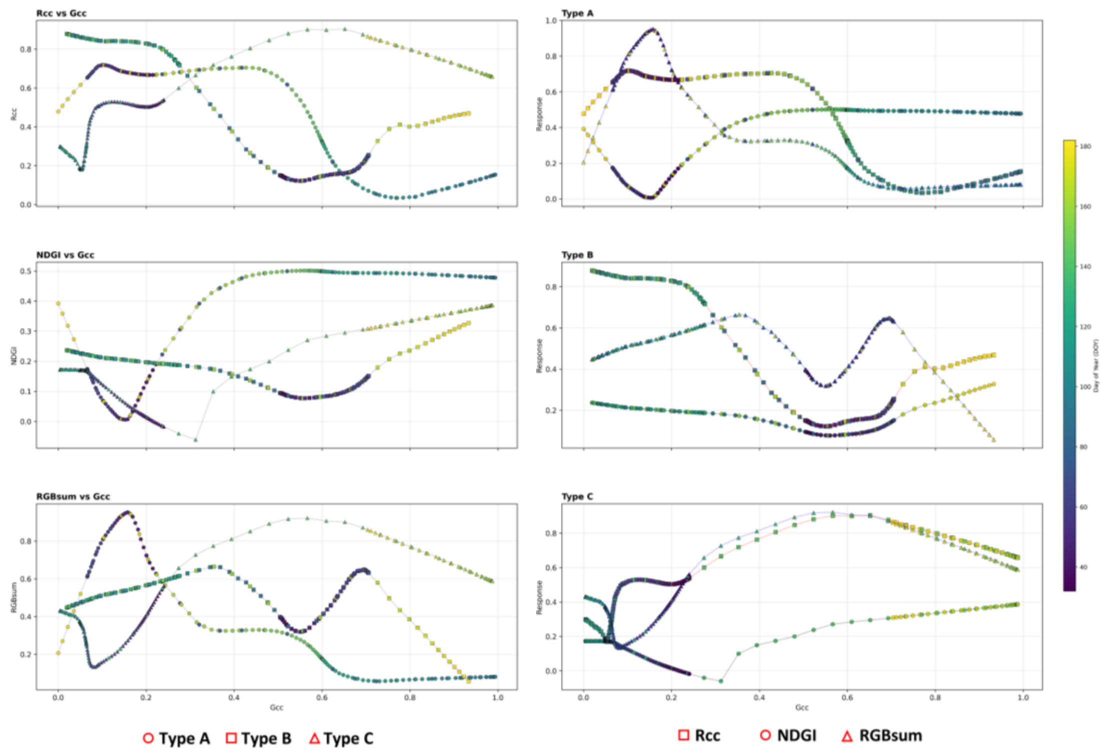

Fig. 3(c)- Comparison (left column) and Mechanism (right column) scatterplots with Gcc as the anchor variable. Chromatic and structural properties of Rcc, NDGI and RGBsum show their relative dominance and contextual importance as proxies for the distinct spring phenological cycles across the three canopy types

3.4. Limitations for time-series representation and transition to relational analysis

Time-series representations described seasonal trajectories but treated variables independently, emphasizing temporal structure over inter-variable relationships. Given that canopy development arises from coupled structural, biochemical, and radiative processes these representations obscured inter-variable relationships, many studies had noted limitations in single-index trajectory based phenological analysis (Dronova and Taddeo, 2022). Phase-space analysis, using 'comparison' and 'mechanism' plots (Fig. 3(c)) was therefore employed to examine how spectral variables co-evolved, shifting the focus from *timing* to *functional relationships*. The complementary use of *comparison-oriented* and *mechanism-oriented* visualizations allows simultaneous assessment of *inter-canopy variability* and *intra-canopy dynamics* respectively.

3.5. Phase-space expression of canopy-type-specific phenology

Phase-space analysis used Gcc as a common axis of canopy development to examine relationships among spectral variables. While all canopy types progressed toward higher greenness, their trajectories differed fundamentally across canopy types and DoY (Day of Year), indicating that similar greenness levels corresponded to different combinations of structural and optical states. These differences extended previous observations of index divergence (Wang et al., 2020; Yang et al., 2014) and the asynchronous evolution of spectral variables described in the time-series analysis was expressed as differences in trajectorial geometry rather than temporal offset.

3.6. Trajectory structure and inter-variable relationship

The canopy types differ primarily in the degree and nature of coupling between Gcc and other metrics. Type A canopies exhibited tightly coupled, nonlinear responses in both Rcc and RGBsum, characterized by rapid declines at intermediate greenness levels, indicating a coordinated shift from woody reflectance to pigment absorption, accompanied by rapid structural closure and reduced canopy brightness. Type C canopies showed smoother and more gradual trajectories, reflecting more synchronized structural and optical development, consistent with the absence of abrupt transitions in the underlying canopy state. Type B canopies occupied an intermediate regime, with less constrained, non-monotonic behaviour, particularly in RGBsum, suggesting variable coupling driven by transient canopy states., i.e. early white flowering stages leading to more complex and less predictable trajectories. Such variable coupling between spectral signals had been observed where phenological metrics responded differently based on canopy structure and composition (Thapa et al., 2021).

3.7. Differential sensitivity of spectral parameters towards canopy metamorphosis

The relationship between other variables and Gcc were strongly nonlinear, with clear evidence of saturation at higher greenness levels. NDGI exhibited a monotonic increase followed by stabilization, reflecting the saturation of canopy structure. In contrast, Rcc and RGBsum exhibited sharper responses and plateaus, indicating reduced sensitivity at higher canopy density. It is clear that the sensitivity of spectral indices to phenological change is not uniform across the season. Early and intermediate stages are characterized by high responsiveness, while later stages converge toward similar spectral states, reducing the ability to distinguish canopy conditions based on individual indices, similar to previously observed reduced discriminatory power at peak canopy development (Yang et al., 2022). This saturation behaviour in time-series representations becomes explicit in phase-space through the compression of trajectories at high greenness.

The indices exhibited distinct sensitivities in capturing canopy dynamics. NDGI showed stable and monotonic behaviour, indicating robustness as a structural proxy that was relatively insensitive to illumination and radiative variability. Rcc responded strongly to pigmentation, chlorophyll maturation and tissue yellowing while RGBsum reflected strong sensitivity to canopy structure, illumination conditions, and radiative transfer effects. These differences underscore that the indices captured complementary, non-redundant aspects of canopy dynamics.

3.8. Interpretation of spectral decoupling and multi-dimensional phenological space

The phase-space trajectories revealed distinct hysteresis-like path-dependent behaviour, where similar greenness values corresponded to different canopy states, depending on the stage of development. Studies (Dronova and Taddeo, 2022; Wong et al., 2022) had confirmed that canopy dynamics occupy a decoupled multi-dimensional spectral space, jointly defined by the configuration of multiple spectral signals, capturing both the direction and the pathway of phenological change. Integrating structural (NDGI), absorption-sensitive (Rcc), and radiative (RGBsum) metrics would enable a more mechanistic interpretation of canopy dynamics.

3.9. Scope and context of this analysis

The observed heterogeneity in canopy phenological trajectories has important implications for satellite-based spatially aggregated estimates of spring onset and early-season vegetation dynamics devoid of tree-level variability, similar to widely reported scale mismatches between satellite and ground measurements (Donnelly et al., 2022; Klosterman et al., 2014)

This study focused on transitions at the scale of individual tree canopies using PhenoCAM imagery. By isolating early spring dynamics, it emphasized on the sequence and timing of canopy changes while enabling direct comparison between tree-level signature and spatially aggregated satellite observations, highlighting scale-dependent differences in phenological interpretation of complex heterogenous canopies of tropical deciduous forests of India.

4. Conclusions

The findings of this study sit within the larger context of terrestrial-ecosystem-monitoring, with the help of near range PhenoCAM based imaging. Using RGB chromatic coordinates with an IR-based structural index, we built upon existing PhenoCAM-based approaches to isolate canopy-type-specific response patterns, identify nonlinearities in spectral change, and examine the relative influence of structural and biochemical controls in multi-layered canopies and species rich heterogenous ecosystems like tropical forests of India, while validating our findings against previous studies done across different biomes, spatial and temporal regimes.

Distinct spring phenological pathways were characterized by differences in pheno-phase sequences, transition timing, and inter-variable coupling. These differences emerged not only as temporal offsets but as fundamentally different trajectories in spectral phase-space framework, reflecting canopy-type-specific interactions among structural development, pigment dynamics, and radiative processes, confirming that phenological development is inherently multi-dimensional and cannot be fully characterized using single indices or time-series change detection analysis. Moreover, satellite pixel-scale signals represented spatially aggregated responses which masked early-season transitions and mixed phenological states, potentially introducing uncertainty in the estimation of spring onset and ecosystem productivity. This highlights a fundamental scale mismatch between tree-level phenological processes and pixel-integrated remote sensing metrics widely used in Earth system analyses.

Our analysis was focused on spring transitions of 2023, and extending this framework across complete growth cycles would enable direct comparison between spring and autumn dynamics, providing a more comprehensive understanding of species-specific development pathways. Integration of contemporaneous AWS-based microclimatic and edaphic measurements would be the next big improvement. Explicit linkage between multispectral canopy observations and their environmental drivers would enable process-level interpretation of canopy behaviour and help incorporate phenological data into climate modelling initiatives.

High resolution monitoring of phenological behaviour, under the influence of micro-climatic conditions, is a key step towards understanding physiological processes like photosynthesis, evapotranspiration and primary productivity. Such processes make tropical forests a hotspot for scientific research due their role as key regulators of climate change.

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Conflict of interest statement

The authors declare no conflict of interests relevant to this study.

Open research and data availability statement

The PhenoCAM data used for this study is proprietory in nature, hence not publicly available. However, it might be shared by the discretion of the author in case of special requests.

The satellite dataset that supported this study is publicly available as Sentinel-2 MSI Level 2A(SR) Harmonized data on Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR_HARMONIZED).

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