Phenological Patterns of Woody Plant Species in a Tropical Dry Forest, Bannerghatta National Park, Bengaluru

Balasubramanya Sharma[1, *], Akshaya Kumar V G[1], Poorvashree P[1], Vinaya Kumar K H[1], Noorunissa Begum[2], Debabrata Saha[2], and Suresh H S[3]

[1]Environmental Management and Policy Research Institute

“Hasiru Bhavana”, Doresanipalya Forest Campus

Vinayakanagara Circle, J.P Nagar 5th Phase

Bengaluru - 560078, India

Phone: +91-80-26490746/47, Mobile: 9342006314

[*]Corresponding author: sharmabalasubramanya@gmail.com

[2]Centre for Conservation of Natural Resources

The University of Trans-Disciplinary Health Sciences and Technology

74/2, Jarakabande Kaval

Post Attur via Yelahanka

Bengaluru - 560064, India

[3]Centre for Ecological Sciences and Divecha Centre for Climate Change

Indian Institute of Science

Malleswaram

Bengaluru - 560012, India

Abstract

Phenology is the study of the timing of recurring natural stages in the life cycle of an organism. These natural stages, such as the plant's reproductive cycles, are being affected by the changing climate. The current study aims to understand the effect of weather parameters on the phenology of dry forests in Bannerghatta National Park. Two transects with 504 reproductively mature individuals were monitored monthly for vegetative and reproductive phenologies. Different phenophases were scored as a percent of the canopy quantitatively. Weather parameters and soil moisture were estimated for each month. Data were analysed for the observed general pattern of phenology and the influence of climate on different phenophases. The intense phenological activity was observed during the dry season. Community-level leaf initiation and flower initiation were positively correlated with maximum temperature ($r_s = 0.524$, $p<0.05$ for leaf initiation; $r_s = 0.586$, $p<0.05$ for flower initiation) and sunshine hours ($r_s = 0.552$, $p<0.01$ for leaf initiation; $r_s = 0.546$, $p<0.05$ for flower initiation). Leaf and flower initiations were highly correlated and significant ($r_s=0.926$, $p<.001$). Principal Component Analysis of weather parameters reveals that 88.5% of the variance is accounted for by the first three principal components. Principal component regression of the first three principal components and the phenophase intensities confirms a positive correlation with leaf initiation (multiple $R = 0.716$, $p<0.01$) and flower initiation (multiple $R = 0.638$, $p<0.05$). Our studies reaffirm that moisture-related factors are the major drivers of phenophase intensities, and changes in these factors could alter the timing of leafing, flowering, and fruiting.

Keywords: *Phenophase, Deciduous, Tropical dry forests, Bannerghatta, Principal Component Analysis*

Introduction

Phenology is the study of the appearance of an organism at a given point in time at the population level and its response to climate change. The vegetative (leafing) and reproductive (flowering, fruiting) phases of a plant are affected by seasonal variations in the environment. Factors that influence phenology could be grouped under two headings: viz., proximate or ultimate causes (Lobo et al., 2003). Proximate (oncoming) causes are short-term environmental factors such as changing precipitation, fluctuating temperatures, and irradiance, whereas ultimate (absolute) causes are the biotic evolutionary forces such as avoidance of herbivory and pollinator attraction. Proximate causes - changes in precipitation (Bao et al., 2021; Barrett & Brown, 2021; Bendix et al., 2006; Opler et al., 1976), temperature (Caroline E. G. Tutin & Fernandez, 1993; Jagadish et al., 2016; Meng et al., 2020), and photoperiod (Adole et al., 2019; Borchert & Rivera, 2001; Van Schaik, 1986; Wright & van Schaik, 1994) - lead to an alteration in the timing of leafing, flowering, and fruiting. Biotic factors (ultimate causes) such as herbivory (Aide, 1993; Collinge & Louda, 1989; Meineke et al., 2021; Murali & Sukumar, 1993; van Schaik et al., 1993) and pollinators (Appanah, 1993; Forrest, 2015; Gentry, 1974; Suhaida et al., 2018) also influence phenology, along with abiotic factors (proximate causes). Each of the abiotic and biotic factors has a role, but it is the interplay of all the factors that influence the expression of a phenophase. The outcome of the changes in the timing of recurring events could lead to phenological mismatches (Lameris et al., 2018; Renner & Zohner, 2018) among interacting species and this could help understand the vulnerability of species to changing climate (Miller-Rushing et al., 2010).

Climate change has gained prominence (Veríssimo et al., 2014), and studies have been undertaken to assess its impact on phenology (Kushwaha & Singh, 2005; Soibam Lanabir Singh & U. K. Sahoo, 2019). Climate change has shown advancement in the phenological cycle and prolonging of growth periods in multi-purpose trees of north-western mid-Himalayan regions (Panda et al., 2021), advancement of leaf unfolding in broad-leaved trees in Switzerland (Meier et al., 2021), a decrease in species' participating in flowering and fruiting in Southeast Asia (Numata et al., 2022), and advancement of the growing season in the Kumaun Himalaya (Singh P & Negi G C S, 2016). Plants are not immune to climate change; introduced species may be unaffected (Manes et al., 2021), whereas endemic species are highly susceptible. In the current scenario of a changing climate, community-level phenological monitoring becomes all the more important, either using remote sensing technology (Ayushi et al., 2022) or through periodic field visits for understanding the variations in phenophases.

Tropical forest phenology is governed by rainfall-related events. Leaf phenology in evergreen and deciduous forests is dependent on regional rainfall patterns (Aravind et al., 2013; Hannah, 2011; Nanda A, 2013; Saha & Sundriyal, 2010; Surajit Ghosh et al., 2019). Temperatures do affect plant growth, with warmer temperatures increasing the rate of phenological development (Barrett & Brown, 2021; Jerry L. Hatfield & John H. Prueger, 2015). The onset of flowering and peak flowering in most forest types are implicated in the increase in temperatures (Manas Ranjan Mohanta et al., 2020; Mustaqeem Ahmad et al., 2021; Zhen Wang et al., 2021). Maximum temperatures had a positive influence on the opening of flowers in studies undertaken at Mudumalai and Bhadra, whereas minimum temperatures had a negative influence on flowering (Suresh H S & Nanda A, 2021). In addition to temperatures, photoperiod is also an important environmental cue in germination and the onset of flowering (Rathcke & Lacey, 1985). It has been shown by Adole (Adole et al., 2019) that the dominant factor in vegetation phenology across Africa is photoperiod; the correlation analysis showed that photoperiod had a significant correlation with the start of the season in all vegetation types and geographical regions.

Community-level short-term phenological studies have been undertaken in both dry and moist deciduous forests in India (Bhat, 1992; Bhat D M & Murali K S, 2001; Murali & Sukumar, 1993; Nanda et al., 2011; Prasad & Hegde, 1986). Most of these studies focus on the effects of rainfall and temperature on leafing, flowering, and fruiting phenophases. The data on the effect of sunshine and radiation on phenophases is lacking in India due to the paucity of monitoring stations with sensors that capture sunshine hours and irradiance. Here we present the 2-year observations on leafing, flowering, and fruiting of trees, considering the weather data from an automatic weather station installed at BNP. We attempted to answer the following questions:

1. When do the intense periods of vegetative and reproductive phenophases occur, and are these patterns identical to those in other dry deciduous forest regions?
2. What are the environmental factors that influence the phenophases either independently or in combination with others?

The study considers monthly phenological observations undertaken at the dry deciduous forest of BNP for the 2 years' period from July 2019 to June 2021. This first-of-its-kind study on the phenology of dry deciduous forests in the Bannerghatta National Park (BNP) is an attempt to understand the effect of seasonal variability on leafing, flowering, and fruiting phenophases.

Materials and Methods

Study Area

The study was conducted in Thalewood House and Bugarikallu localities of BNP. BNP has an area of 260.51 sq. km. BNP is surrounded by Bangalore city, the Kodihalli, Harohalli, and Kanakapura regions of Karnataka, and borders the Tamilnadu state. The terrain is highly undulating and interspersed with barren rocks and valleys (Raju R, 2014). The rocks are muscovite granite gneiss or biotitic granite gneiss and named "Peninsular Gneiss" based on the abundance and deposition of ferro minerals. The elevation ranges from 700 meters to 1030 meters above sea level. Rainfall in BNP is from both the southwest and northeast monsoons.

The weather parameters of the study area such as rainfall, temperature, sunshine hours, humidity, and solar radiation were downloaded and compiled into monthly data. The monthly data (Figure 1) was used for analysis along with the phenophases.

Vegetation

The vegetation in BNP varies from dry thorn to dry deciduous forests with patches of mixed moist forests. The most common canopy tree species include *Anogeissus latifolia, Polyalthia cerasoides, Acacia chundra, Diospyros melanoxylon, Dalbergia lanceolaria, Vitex altissima, Terminalia bellirica, Strychnos potatorum, Terminalia paniculata, and Buchanania axillaris.* The common understorey species include *Ixora arborea, Erythroxylon monogynum, Maytenus emarginata, Phyllanthus polyphyllus, Grewia orbiculata, Bauhinia racemosa, Cassia fistula, Holarrhena antidysenterica, Ochna obtusata, and Canthium parviflorum.* In addition to the canopy and understorey species, woody climbers and stragglers such as *Ventilago maderaspatana, Hiptage benghalensis, Ziziphus oenoplia, Acacia pennata, Mimosa rubicaulis, Pterolobium hexapetalum* all form part of the vegetation. Invasive species such as *Chromolaena odoratum* and *Lantana camara* also are included in the understorey.

Methods

Reproductively mature woody individuals with clearly visible crowns were identified and marked along either side of transects for around 3 km. A total of 504 tagged individuals comprising 84 species belonging to 37 families (254 individuals in the Thalewood House locality and 250 individuals in the Bugarikallu locality) were monitored. The vegetative and reproductive phenophases of the 504 individuals were observed every month for a period of 2 years, from July 2019 to June 2021. But, due to COVID-19, data could not be collected for two months (April and May 2020).

Two transects were laid, one in the Thalewood House locality and the other in the Bugarikallu locality of BNP; the distance between the two transects is around 4 km. Each transect was laid around one-hectare permanent preservation plots (Kakkar et al., 2018) at Thalewood House and Bugarikallu. Vegetative phenology included the following leafing phenophases: 1. Leafless; 2. leaf initiation; 3. expanding leaves; 4. mature leaves; and 5. senescent leaves. Reproductive phenology included flowering, comprising the following: 1. Flowerless; 2. flower buds; 3. open flowers; 4. mature flowers; and 5. senescing flowers and fruiting comprise the following: 1. Fruitless; 2. initiating fruits; 3. young fruits; 4. mature fruits; and 5. falling fruit phenophases. Each of these stages was scored between 0 and 100%. The monitoring was done with the help of a Nikon Aculon A211, 10 mm x 50 mm optical binocular.

Soil samples were collected manually at a depth of 0-30 cm using a soil auger at ten different points along the transect. The soil moisture content was estimated using the oven-dry method (Bureau of Indian Standards (BIS), 1973). The average of the 10 samples is the soil moisture content of the transect for a given month.

The weather data for BNP was obtained from the automatic weather monitoring stations installed at Bugarikallu. The weather parameters, such as temperature, sunshine hours, humidity, solar radiation, wind speed, and wind direction, were downloaded from the FTP servers of Karnataka State National Disaster Monitoring Stations. Rainfall data were obtained from the Dyavasandra rain gauge near Bugarikallu.

Data analysis

The phenophase observations in the field were noted down in a standard format. The combined data of both Thalewood House and the Bugarikallu locality were taken for analysis. The intensity of a phenophase was used as a measure and was defined as the number of species participating in a given phenophase divided by the total number of species, multiplied by the average extent of a given phenophase on the canopy.

Spearman's correlations were performed to assess the relation between weather parameters such as rainfall and temperature on the phenophases.

Principal Component Analysis (PCA) was performed using the weather parameters total rainfall (TRF), number of rainy days (NRD), percent soil moisture (SM), maximum temperature (Max.T °C), minimum temperature (Min.T °C), percent humidity (Hum), and sunshine hours (Sun.Sh.). The loadings from the PCA were used for regressions with different phenophases. Correlations, PCA, and regressions were performed using PAleontological STatistics software (PAST) (Hammer et al., 2001).

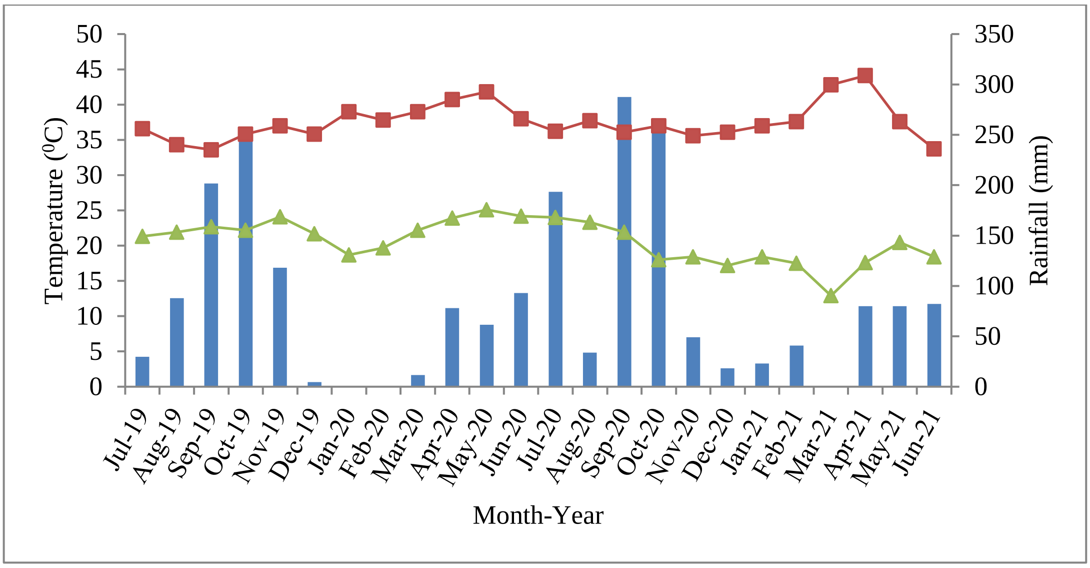

Figure. 1: Total monthly rainfall (mm) and mean monthly maximum (■), mean monthly minimum (▲) temperature (^{0}C) at BNP during July 2019 to June 2021

Results

Community patterns of phenology

Vegetative phenology

The leafless stage started in the month of November and reached its maximum in the early part of the March month (Figure 2). Leaf initiation in most species occurred during the dryer months when there was less soil moisture. Leaf initiation started in January and peaked in March. Mean leaf elongation intensity was maximum during April, whereas senescence was maximum during January (Figure 2).

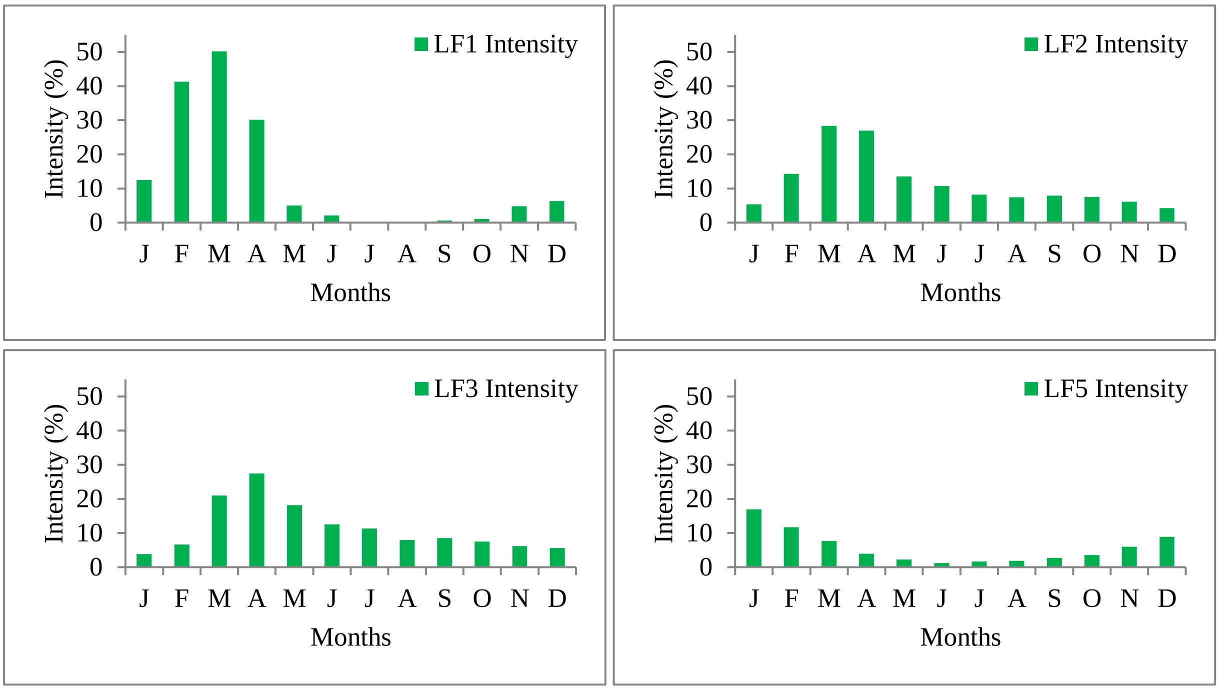

Figure 2: Leafless stage (LF1), Leaf initiation (LF2), Leaf elongation (LF3) & Leaf senescence (LF5) in BNP

Reproductive phenology

Flower initiation is dependent on many cues. Flower initiation in most species occurred during the summer and peaked in April. Flower maturation peaked in April and May. Interestingly, flower dehiscence (FL5) peaked in April (Figure 3).

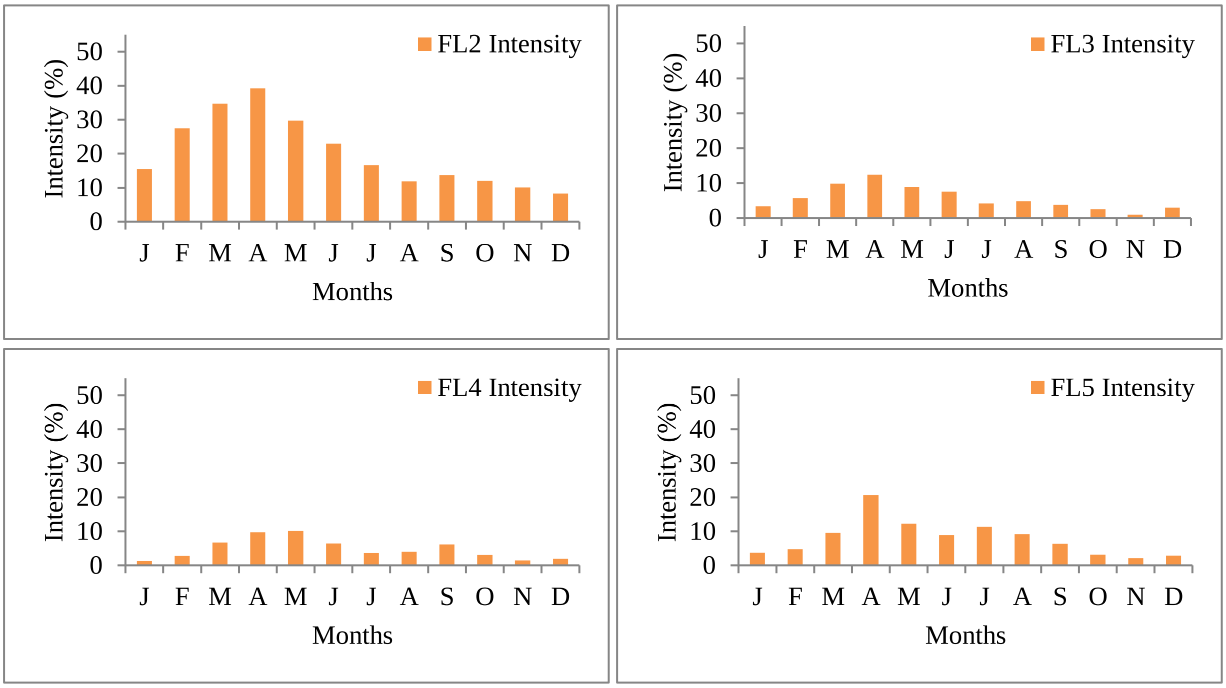

Figure 3: Flower initiation (FL2), Flower opening (FL3), Flower maturation (FL4) & Flower dehiscence (FL5) in BNP.

Fruit initiation (FR2) peaked during May, with maturation (FR4) occurring primarily during September. Fruit dehiscence (FR5) was seen throughout the year but primarily during February before the onset of leaf and flower initiation (Figure 4).

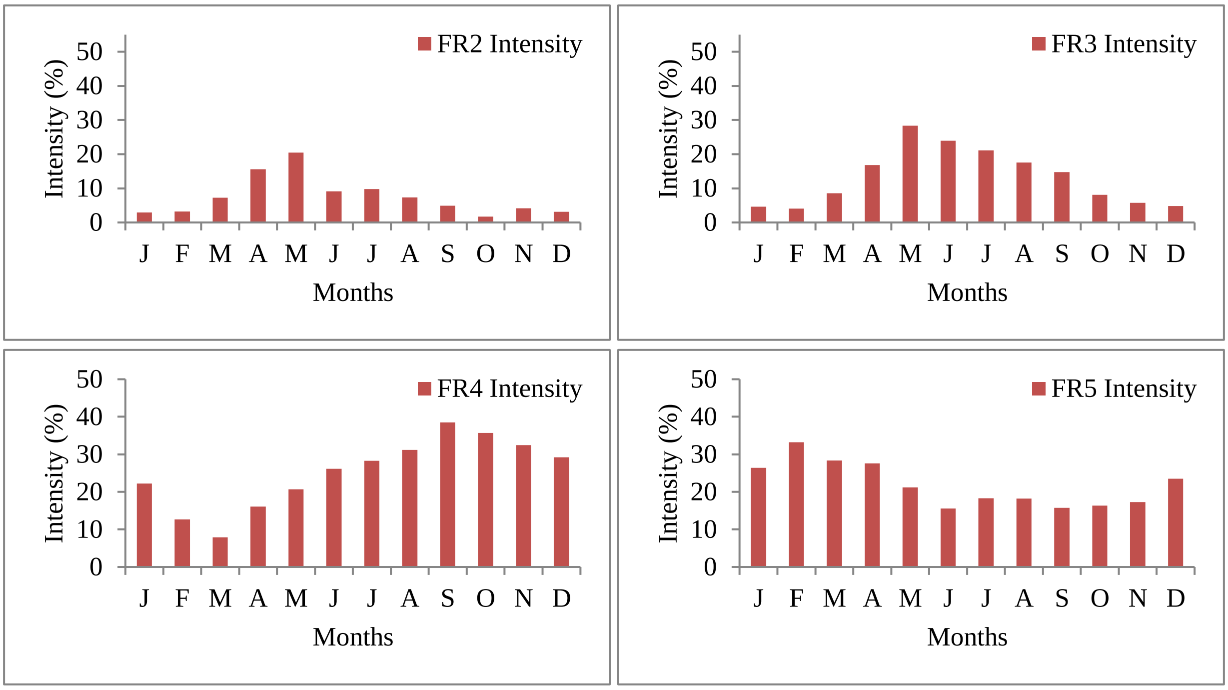

Figure 4: Fruit initiation (FR2), fruit elongation (FR3), fruit maturation (FR4) & fruit dehiscence (FR5) in BNP.

Factors influencing phenology

Vegetative phenology

a) Leaf initiation: The maximum temperature had a significant positive influence on leaf initiation during the corresponding (rs=0.524, $p<.05$) and one-month lag periods (rs=0.614, $p<.05$); similarly, sunshine hours also showed a significant positive influence on leaf initiation during the corresponding months (rs=0.552, $p<.01$) whereas rainfall (rs=-0.767, $p<.001$), number of rainy days (rs=-0.774, $p<.001$), and soil moisture content (rs=-0.882, $p<.001$) had a significant negative influence during the two-month lag period. The intensity of leaf initiation versus maximum temperature is shown in Figure 5; the maximum temperature had a significant positive influence on leaf initiation (see supplementary data).

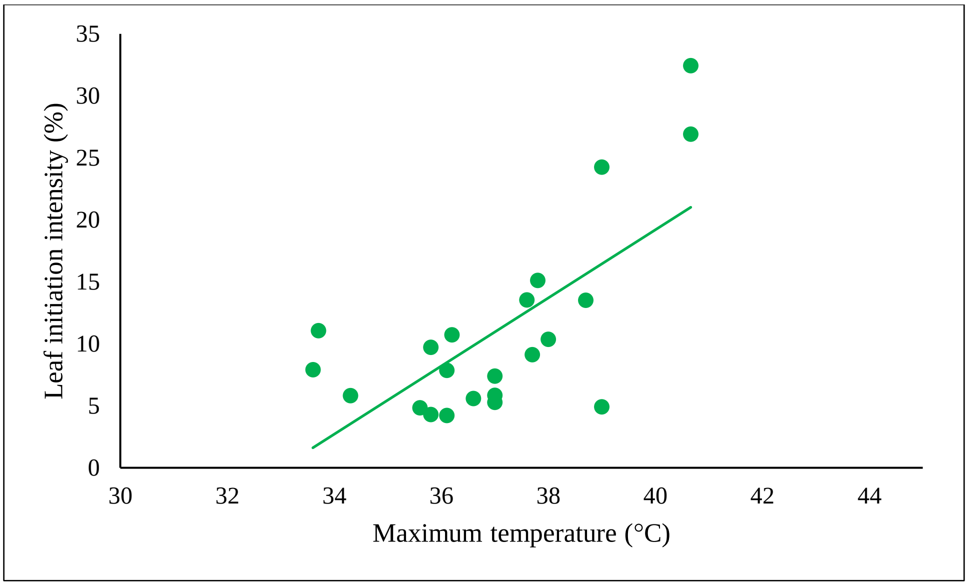

Figure 5: Intensity of leaf initiation (LF2) in relation to maximum temperature in BNP

b) *Factors influencing leaf elongation and leaf maturation:* Minimum temperature and sunshine hours had a significant positive influence (rs=0.558, p<.01 for minimum temperature; rs=0.551, p<.01 for sunshine hours) on leaf elongation during corresponding months.

Rainfall, number of rainy days (NRD), and soil moisture (SM) content all had a significant positive influence (rs=0.543, p<.01 for rainfall; rs=0.625, p<.01 for NRD; rs=0.587, p<.01 for SM) on leaf maturation, whereas maximum temperature had a negative influence (rs=-0.651, p<.01) during the corresponding months. Minimum temperatures had a positive influence during a two-month lag period (rs=0.541, p<.05) on leaf maturation.

Reproductive phenology

a) *Flower initiation:* The maximum temperature positively influenced flower initiation (rs=0.586, p<.05). Similarly, sunshine hours also positively influenced flower initiation (rs=0.546, p<.05). Rainfall did not have a significant influence on flower initiation during the corresponding months, whereas during the one-month and two-month lag, there was a significant negative influence of rainfall, NRD, and SM. Similarly, humidity also showed a significant negative influence on flower initiation during the one-month and two-month lags. The number of individuals participating in flower initiation (rs=0.575, p=.005) was positively correlated with maximum temperature, as was the intensity of flower initiation (rs=0.586, p=.0041) (Figure 6).

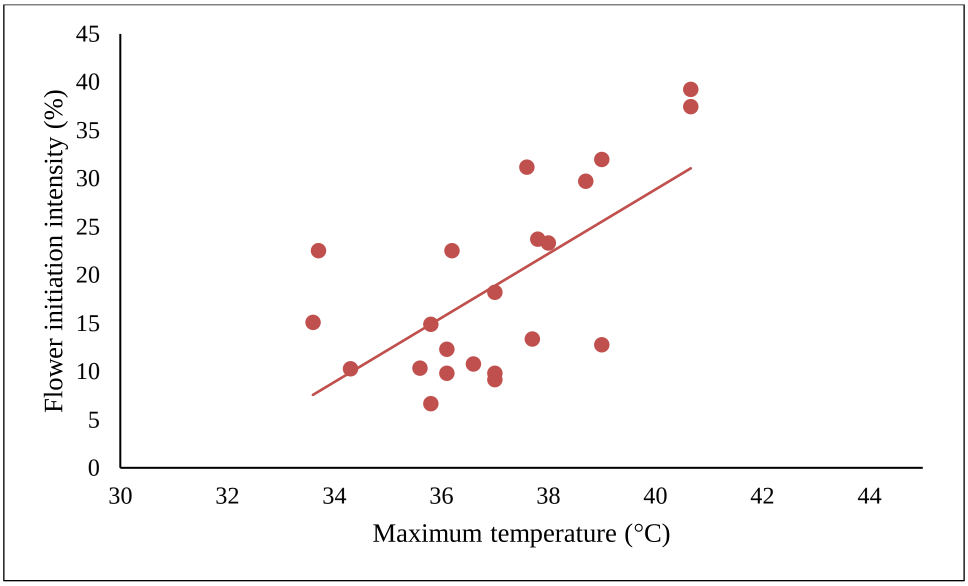

Figure 6: Flower initiating intensity (FL2) in relation to maximum temperature in BNP

Rainfall, NRD, SM, and humidity had a significant negative influence on flower initiation during the one-month and two-month lag periods.

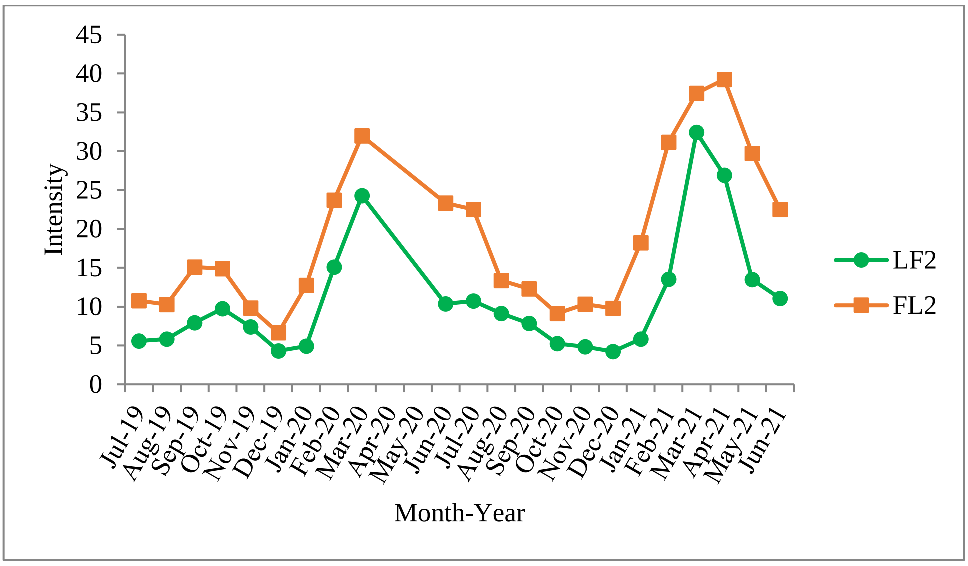

Figure 7: Intensities of leaf initiation (LF2) versus flower initiation (FL2)
(broader base of peaks during 2020 is due to the absence of observations during the months of April & May 2020)

Floral induction usually follows leaf initiation, and there was a strong positive correlation between flower initiation and leaf initiation (rs=0.926, p<.001) (Figure 7).

b) ***Fruit initiation, elongation, and maturation:*** Fruit initiation was not significantly influenced by either of the weather parameters, but a negative significant influence was seen for maximum temperature (rs=0.672, p<.01) and sunshine hours (rs=0.550, p<.01) during the one-month lag and with maximum temperature (rs=0.621, p<.01) during the two-month lag period. Fruit elongation was significantly influenced positively by NRD (rs=0.579, p<.01) and minimum temperature (rs=0.497, p<.05) during the corresponding months, by minimum temperature (rs=0.573, p<.01) and sunshine hours (rs=0.757, p<.01) during a one-month lag, and by maximum temperature (rs=0.545, p<.05) and sunshine hours (rs=0.770, p<.01) during the two-month lag periods. The humidity had a significant negative influence (rs=-0.562, p<.01) on fruit elongation during the two-month lag period.

Rainfall, NRD, SM, and humidity had a significantly positive influence on fruit maturation (rs=0.659, p<.01 for rainfall; rs=0.672, p<.01 for NRD; rs=0.824, p<.01 for SM; rs=0.693, p<.01 for humidity) whereas sunshine and maximum temperature had a significantly negative influence on fruit maturation (rs=-0.498, p<.05 for sunshine; rs=-0.697, p<.01 for maximum temperature). A two-month lag also had a positive response (rs=0.493, p<.05) with the minimum temperature.

Principal Component Analysis (PCA) and Multiple Regressions

Principal Component Analysis

PCA of the weather parameters shows that the first three Principal Components (PCs) were responsible for 88.5% of the variation observed, with PC1 accounting for 52.91%, PC2 for 28.11%, and PC3 for 7.43% (Table 1).

Table 1: Summary of Principal Component Analysis

PC	Eigenvalue	% variance
1	3.70432	52.919
2	1.96796	28.114
3	0.520605	7.4372
4	0.499654	7.1379
5	0.152154	2.1736
6	0.0877213	1.2532
7	0.0675838	0.96548

PC1 had a positive contribution from TRF, NRD, SM, and humidity (Table 2), with SM contributing the highest (0.912), while PC2 had a positive contribution from the minimum temperature (0.90) and sunshine hours (0.77). Maximum temperature (0.58) was the major contributor for PC3 (Table 2).

The Principal Component Scores (PCS) of PC1, PC2, and PC3 obtained from the PCA were used for the regression analysis with the dependent variable, the phenophase.

Table 2: The first three loadings (correlation values) of PCA

Weather parameters	PC 1	PC 2	PC 3
Total Rainfall (mm)	0.849	0.351	0.091
Number of rainy days (days)	0.861	0.377	-0.159
Average Soil moisture (%)	0.913	0.249	0.195
Maximum temper (°C)	-0.673	0.430	0.580
Min.T (°C)	-0.015	0.905	-0.011
Humidity (%)	0.834	-0.181	0.140
Sunshine (hrs)	-0.509	0.776	-0.303

Multiple regressions

Multiple regressions/Principal Component Regressions (PCR) were performed with the first 3 PCS against the phenophases, leaf initiation, flower initiation, and fruit elongation.

i. ***Leaf initiation:*** There was a significant positive correlation with LF2 (multiple R=0.716, p<.01) during the corresponding months. PC1 had a negative influence and was significant (Coeff. PC1=-2.307, p<.01) whereas PC2 had a positive influence and was significant (Coeff. PC2=2.89, p<.01) on leaf initiation (please see supplementary data). In the case of a one-month lag, there was a significant positive correlation (multiple R=0.639, p<.05) but only PC1 had a negative influence and was significant (Coeff. PC1=-2.64, p<.01). Similarly, in the case of a two-month lag, there was a significant positive correlation (multiple R=0.686, p<.05) with both PC1 & PC2 having a negative influence and being significant (Coeff. PC1=-1.685, p<.05, Coeff. PC2=-2.717, p<.05).

ii. ***Flower initiation:*** Flower initiation was significantly influenced by the 3 PCS during the corresponding month (multiple R=0.638, p<.05), one-month lag (multiple R=0.750, p<.01), and two-month lag (multiple R=0.865, p<.01) periods. In the case of corresponding months, PC1 (Coeff. PC1=-2.80, p<.01) had a negative influence and PC2 (Coeff. PC2=2.94, p<.05) had a positive significant influence; in the case of a one-month lag, only PC1 (Coeff. PC1=-3.87, p<.01) had a negative influence that was significant; in two-months lag, PC1 & PC2 were statistically significant (Coeff. PC1=-3.08, p<.01; Coeff. PC2=-3.61, p<.01) (please see supplementary data).

iii. ***Fruit elongation****:* A one-month lag showed a strong correlation (multiple R=0.752, p<.01) that was significant, with a significant contribution by PC1 (Coeff. PC1=-1.93, p<.05) and PC2 (Coeff. PC2=4.538, p<.01). A two-month lag also showed a strong correlation (multiple R=0.802, p<.01) and significant contributions by PC1 (Coeff. PC1=-3.054, p<.01) and PC2 (Coeff. PC2=3.148, p<.01).

Discussion

The phenology of dry forests is interesting, as dry forests across the globe experience moisture stress for varying periods (Murphy & Lugo, 1986). Dry forests are one of the least studied, though they account for a large proportion of the biome both around the globe and in India (Kushwaha & Singh, 2005; Miles et al., 2006). The phenology of trees in the dry tropics is influenced by soil moisture. A lowering of precipitation, the start of the dry season, and a reduction in the soil moisture content mark the period of leaf and flower initiation in the dry tropics. The phenology of trees in BNP is no different and is also similar to the studies undertaken elsewhere (Elliott et al., 2006; Nanda et al., 2020; Prasad & Hegde, 1986).

Vegetative phenology and influencing factors

Vegetative phenology is important as leaves are the main parts of the plant where photosynthesis and respiration take place. Leaf initiation in BNP starts during January and peaks during March and April. Studies in Bhadra wildlife sanctuary (Nanda A, 2013) show leaf initiation at its maximum during April, whereas in Mudumalai (Suresh & Sukumar, 2018) it is from February to April. In the subtropics, leaf initiation is during February and March in Assam (Devi et al., 2019) whereas in Manipur it is during March to April (Kikim A & Yadava P S, 2001). Leaf shedding starts at the end of November and peaks during January in BNP, whereas the leafless stage peaks during March. Leaf shedding seen in BNP is similar to studies in dry deciduous regions of Bhadra wildlife sanctuary (Nanda A, 2013; Nanda A et al., 2015) in the Western Ghats and in the subtropics (Devi et al., 2019; Kikim A & Yadava P S, 2001).

The factors influencing leaf initiation intensities in BNP are low soil moisture, photoperiod (sunshine hours), and maximum temperature; minimum temperatures positively influenced the number of species participating in leaf initiation. Leaf expansion is influenced by minimum temperatures along with photoperiod. This contrasts with studies in dry deciduous forests in the Bhadra wildlife sanctuary (Nanda A et al., 2015) where leaf expansion was positively influenced by maximum temperature. Leaf maturation is positively influenced by rainfall, and soil moisture and negatively influenced by maximum temperatures.

Reproductive phenology and influencing factors

Reproductive phenology includes flowering and fruiting processes that are dependent on weather parameters as well as on pollinators. Flower initiation or induction is also dependent on endogenous control (juvenile or mature) and indirectly through environmental factors, but once the tree is mature, it might or might not flower every year (Koelmeyer K O, 1959).

Flower initiation starts simultaneously with leaf initiation and is observed from January, and peaks during April with a minor peak in September, which is comparable to other studies (Kikim A & Yadava P S, 2001; Nanda et al., 2011; Sundarapandian, S. M et al., 2005) in tropical and subtropical regions. Flower maturation peaks during May with an additional small peak during September as also observed in studies undertaken in the Kodayar forest region of western ghats (Sundarapandian, S. M et al., 2005).

The factors that positively influence flower initiation in BNP are maximum temperature and photoperiod during corresponding months. Rainfall, number of rainy days, Soil moisture, and humidity, all of these negatively influence flower initiation during the two-month lag period. This is similar to studies undertaken at dry deciduous forests in Bhadra wildlife sanctuary (Nanda et al., 2011) and Mudumalai dry deciduous forests (Murali & Sukumar, 1994) where flower initiation is negatively influenced by rainfall (two-month lag period-flowering preceding raining). Flower initiation in contrast to leaf initiation (where minimum temperature increased number of species participating) is influenced by maximum temperatures – the number of species participating as well as the intensities were positively influenced. Flower initiation was positively influenced by both maximum and minimum temperatures in studies undertaken by Sunderpandian in the Kodayar forests of the Western Ghats (Sundarapandian, S. M et al., 2005).

Principal Component Analysis and Regression

A combination of weather parameters controls phenological events (Adole et al., 2019). Our observations also show that several weather factors play a role in influencing the phenophases. To better understand the factors responsible, Principal Component Analysis (PCA), a dimensionality reduction method, was used for the analysis of six weather parameters (Rainfall, number of rainy days, maximum temperature, minimum temperature, humidity, and sunshine hours) along with soil moisture content.

The PCA showed that 88.5% of the variation is accounted by three principal components PC1, PC2, and PC3. PC1 accounts for 53% of the variation whereas PC2 accounts for 28% and PC3 for 7.5% of the variation. The first principal component (PC1) was strongly correlated with rainfall, number of rainy days, soil moisture content, and humidity, suggesting that these four variables vary together. The first principal component correlates most strongly with soil moisture content. The correlation value of 0.913 implies that the first principal component is primarily a measure of soil moisture content. Similarly, the second principal component increases with increasing minimum temperatures and sunshine hours. The second principal component correlates most strongly with the minimum temperature. The correlation value of 0.905 implies that the second component is primarily a measure of minimum temperature.

Principal component regression (PCR) of three principal component scores (PC1, PC2, and PC3) was performed with the phenophase intensities under different time periods. PC1 had negative values which was significant for both leaf initiation and flower initiation during corresponding, one-month and two-month lag periods. In the case of fruit elongation, PC1 had negative values for one-month and two-month lag periods and was significant. PC2 had positive values that were significant for both leaf initiation and flower initiation during corresponding months. Based on the variables in the PC1, it could be stated that moisture-related factors (rainfall, number of rainy days, soil moisture content, and humidity) have a negative influence on leaf and flower initiation, while minimum temperature and photoperiod have a positive influence on leaf and flower initiation.

Our studies underpin soil moisture, maximum temperatures, and sunshine hours as the underlying major factors, which is in line with other studies in dry deciduous tropical trees. Unravelling the phenological variations in BNP due to weather parameters requires long-term monitoring, and this could pave the way for a better understanding of the effect of changing climate on phenophases.

Acknowledgements

We thank the Department of Science and Technology, Government of India for the financial support under the Strategic Programmes, Large Initiatives, and Coordinated Action Enabler (SPLICE) project. We are indebted to Karnataka Forest Department for the permissions provided to undertake this study as well as for the manpower provided during our field visits to BNP. We also thank the EMPRI scientific staff, Dr. Manjunatha M, Research Scientist; Dr. Pavithra P N, Research Scientist; and Ms. Nethravathi M, Junior Research Fellow for their help and support during field visits to BNP. We are grateful to Dr. A K Chakravarthy, Research Scientist, EMPRI for correcting the manuscript. The logistical support from EMPRI is gratefully acknowledged.

References

Adole, T., Dash, J., Rodriguez-Galiano, V., & Atkinson, P. M. (2019). Photoperiod controls vegetation phenology across Africa. *Communications Biology*, *2*(1), 391. https://doi.org/10.1038/s42003-019-0636-7

Aide, T. M. (1993). Patterns of Leaf Development and Herbivory in a Tropical Understory Community. *Ecology*, *74*(2), 455–466. https://doi.org/10.2307/1939307

Appanah, S. (1993). Mass flowering of dipterocarp forests in the aseasonal tropics. *Journal of Biosciences*, *18*(4), 457–474. https://doi.org/10.1007/BF02703079

Aravind, N. A., Ganeshaiah, K. N., & Shaanker, R. U. (2013). Indian monsoons shape dispersal phenology of plants. *Biology Letters*, *9*(6), 20130675. https://doi.org/10.1098/rsbl.2013.0675

Ayushi, K., Babu, K. N., Reddy, C. S., Mayamanikandan, T., Barathan, N., Debabrata, B., & Ayyappan, N. (2022). Remote sensing based characterisation of community level phenological variations in a regional forest landscape of Western Ghats, India. *Geocarto International*, 1–16. https://doi.org/10.1080/10106049.2022.2112304

Bao, F., Xin, Z., Li, J., Liu, M., Cao, Y., Lu, Q., Gao, Y., & Wu, B. (2021). Effects of the Simulated Enhancement of Precipitation on the Phenology of Nitraria tangutorum under Extremely Dry and Wet Years. *Plants*, *10*(7), 1474. https://doi.org/10.3390/plants10071474

Barrett, A., & Brown, L. (2021). Effects of rainfall, temperature and photoperiod on the phenology of ephemeral resources for selected bushveld woody plant species in southern Africa. *PLOS ONE*, *16*(5), e0251421. https://doi.org/10.1371/journal.pone.0251421

Bendix, J., Homeier, J., Cueva Ortiz, E., Emck, P., Breckle, S.-W., Richter, M., & Beck, E. (2006). Seasonality of weather and tree phenology in a tropical evergreen mountain rain forest. *International Journal of Biometeorology*, *50*(6), 370–384. https://doi.org/10.1007/s00484-006-0029-8

Bhat, D. M. (1992). Phenology of tree species of tropical moist forest of Uttara Kannada district, Karnataka, India. *Journal of Biosciences*, *17*(3), 325–352. https://doi.org/10.1007/BF02703158

Bhat D M & Murali K S. (2001). Phenology of understorey species of tropical moist forest of Western Ghats region of Uttara Kanada district in Southe India. *Current Science*, *81*(7), 799–805.

Borchert, R., & Rivera, G. (2001). Photoperiodic control of seasonal development and dormancy in tropical stem-succulent trees. *Tree Physiology*, *21*(4), 213–221. https://doi.org/10.1093/treephys/21.4.213

Bureau of Indian Standards (BIS). (1973). *IS 2720-2: Methods of Test of Soils, Part 2: Determination of Water Content*. BIS.

Caroline E. G. Tutin, & Fernandez, M. (1993). Relationships between Minimum Temperature and Fruit Production in some Tropical Forest Trees in Gabon. *Journal of Tropical Ecology*, *9*(2), 241–248. JSTOR.

Collinge, S. K., & Louda, S. M. (1989). Influence of plant phenology on the insect herbivore/bittercress interaction. *Oecologia*, *79*(1), 111–116. https://doi.org/10.1007/BF00378247

Devi, N. L., Singha, D., & Das, A. K. (2019). Phenology of deciduous tree species in traditional Meitei homegardens of Barak valley, Assam, northeast India. *Tropical Plant Research*, *6*(3), 365–375. https://doi.org/10.22271/tpr.2019.v6.i3.046

Elliott, S., Baker, P. J., & Borchert, R. (2006). Leaf flushing during the dry season: The paradox of Asian monsoon forests: Dry season leaf flushing. *Global Ecology and Biogeography*, *15*(3), 248–257. https://doi.org/10.1111/j.1466-8238.2006.00213.x

Forrest, J. R. K. (2015). Plant-pollinator interactions and phenological change: What can we learn about climate impacts from experiments and observations? *Oikos*, *124*(1), 4–13. https://doi.org/10.1111/oik.01386

Gentry, A. H. (1974). Flowering Phenology and Diversity in Tropical Bignoniaceae. *Biotropica*, *6*(1), 64. https://doi.org/10.2307/2989698

Hammer, O., Harper, D. A. T., & Ryan, P. D. (2001). PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica*, *4*(1), 9.

Hannah, L. (2011). Phenology. In *Climate Change Biology* (pp. 81–100). Elsevier. https://doi.org/10.1016/B978-0-12-374182-0.00004-2

Jagadish, S. V. K., Bahuguna, R. N., Djanaguiraman, M., Gamuyao, R., Prasad, P. V. V., & Craufurd, P. Q. (2016). Implications of High Temperature and Elevated CO2 on Flowering Time in Plants. *Frontiers in Plant Science*, *7*. https://doi.org/10.3389/fpls.2016.00913

Jerry L. Hatfield & John H. Prueger. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4–10. https://doi.org/10.1016/j.wace.2015.08.001

Kakkar, R., Kumar, K. H. V., Remadevi, O. K., Manjunatha, M., Saritha, B., Sharma, B., Kiranraddi M, H.S. Dattaraja, & H.S. Suresh. (2018). Establishing Permanent Preservation Plots in Bannerghatta National Park for long-term ecological studies to monitor climate change. *My Forest*, *54*(2), 19–34.

Kikim A & Yadava P S. (2001). Phenology of tree species in subtropical forests of Manipur in north eastern India. *Tropical Ecology*, *42*, 269–276.

Koelmeyer K O. (1959). The periodicty of leaf change and flowering in the principal forest communities of Ceylon. *Ceylon Forester*, *4*, 157–189.

Kushwaha, C. P., & Singh, K. P. (2005). Diversity of leaf phenology in a tropical deciduous forest in India. *Journal of Tropical Ecology*, *21*(1), 47–56. https://doi.org/10.1017/S0266467404002032

Lameris, T. K., van der Jeugd, H. P., Eichhorn, G., Dokter, A. M., Bouten, W., Boom, M. P., Litvin, K. E., Ens, B. J., & Nolet, B. A. (2018). Arctic Geese Tune Migration to a Warming Climate but Still Suffer from a Phenological Mismatch. *Current Biology*, *28*(15), 2467-2473.e4. https://doi.org/10.1016/j.cub.2018.05.077

Lobo, J. A., Quesada, M., Stoner, K. E., Fuchs, E. J., Herrerías-Diego, Y., Julissa Rojas, & Guido Saborío. (2003). Factors Affecting Phenological Patterns of Bombacaceous Trees in Seasonal Forests in Costa Rica and Mexico. *American Journal of Botany*, *90*(7), 1054–1063. JSTOR.

Manas Ranjan Mohanta, Suresh H S, & Sudam Charan Sahu. (2020). A Review on Plant Phenology Study in Different Forest Types of India. *Indian Forester*, *146*(12), 1137–1148.

Manes, S., Costello, M. J., Beckett, H., Debnath, A., Devenish-Nelson, E., Grey, K.-A., Jenkins, R., Khan, T. M., Kiessling, W., Krause, C., Maharaj, S. S., Midgley, G. F., Price, J., Talukdar, G., & Vale, M. M. (2021). Endemism increases species' climate change risk in areas of global biodiversity importance. *Biological Conservation*, *257*, 109070. https://doi.org/10.1016/j.biocon.2021.109070

Meier, M., Vitasse, Y., Bugmann, H., & Bigler, C. (2021). Phenological shifts induced by climate change amplify drought for broad-leaved trees at low elevations in Switzerland. *Agricultural and Forest Meteorology*, *307*, 108485. https://doi.org/10.1016/j.agrformet.2021.108485

Meineke, E. K., Davis, C. C., & Davies, T. J. (2021). Phenological sensitivity to temperature mediates herbivory. *Global Change Biology*, *27*(11), 2315–2327. https://doi.org/10.1111/gcb.15600

Meng, L., Mao, J., Zhou, Y., Richardson, A. D., Lee, X., Thornton, P. E., Ricciuto, D. M., Li, X., Dai, Y., Shi, X., & Jia, G. (2020). Urban warming advances spring phenology but reduces the response of phenology to temperature in the conterminous United States. *Proceedings of the National Academy of Sciences*, *117*(8), 4228–4233. https://doi.org/10.1073/pnas.1911117117

Miles, L., Newton, A. C., DeFries, R. S., Ravilious, C., May, I., Blyth, S., Kapos, V., & Gordon, J. E. (2006). A global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, *33*(3), 491–505. https://doi.org/10.1111/j.1365-2699.2005.01424.x

Miller-Rushing, A. J., Høye, T. T., Inouye, D. W., & Post, E. (2010). The effects of phenological mismatches on demography. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1555), 3177–3186. https://doi.org/10.1098/rstb.2010.0148

Murali, K. S., & Sukumar, R. (1993). Leaf flushing phenology and herbivory in a tropical dry deciduous forest, southern India. *Oecologia*, *94*(1), 114–119. https://doi.org/10.1007/BF00317311

Murali, K. S., & Sukumar, R. (1994). Reproductive Phenology of a Tropical Dry Forest in Mudumalai, Southern India. *The Journal of Ecology*, *82*(4), 759. https://doi.org/10.2307/2261441

Murphy, P. G., & Lugo, A. E. (1986). Ecology of Tropical Dry Forest. *Annual Review of Ecology and Systematics*, *17*(1), 67–88. https://doi.org/10.1146/annurev.es.17.110186.000435

Mustaqeem Ahmad, Sanjay K. Uniyal, Daizy R. Batish, Sonia Rathee, Padma Sharma, & Harminder P. Singh. (2021). Flower phenological events and duration pattern is influenced by temperature and elevation in Dhauladhar mountain range of Lesser Himalaya. *Ecological Indicators*, *129*, 107902. https://doi.org/10.1016/j.ecolind.2021.107902

Nanda A. (2013). Canopy trees leaf phenology in tropical dry deciduous and evergreen forests of Bhadra Wildlife Sanctuary Karnataka, India. *African Journal of Plant Science*, *7*(5), 170–175. https://doi.org/10.5897/AJPS12.043

Nanda A, Hiregouja M Prakasha, Hebbalalu S Suresh, & Yelugere L Krishnamurthy. (2015). Leafing phenology of tropical forests of Bhadra wildlife sanctuary, Karnataka, India. *Applied Science Reports*, *12*(1). https://doi.org/10.15192/PSCP.ASR.2015.12.1.3340

Nanda, A., Prakasha, H. M., Murthy, Y. L. K., & Suresh, H. S. (2011). Phenology of Leaf Flushing, Flower Initiation and Fruit Maturation in Dry Deciduous and Evergreen Forests of Bhadra Wildlife Sanctuary, Karnataka, Southern India. *Our Nature*, 11.

Nanda, A., Suresh, H. S., & Murthy, Y. L. K. (2020). Community, Dominant Tree Species Leaf Phenology and Seasonality in a Tropical Dry Forest, India. *International Journal of Environment and Climate Change*, 34–49. https://doi.org/10.9734/ijecc/2020/v10i1130265

Numata, S., Yamaguchi, K., Shimizu, M., Sakurai, G., Morimoto, A., Alias, N., Noor Azman, N. Z., Hosaka, T., & Satake, A. (2022). Impacts of climate change on reproductive phenology in tropical rainforests of Southeast Asia. *Communications Biology*, *5*(1), 311. https://doi.org/10.1038/s42003-022-03245-8

Opler, P. A., Frankie, G. W., & Baker, H. G. (1976). Rainfall as a Factor in the Release, Timing, and Synchronization of Anthesis by Tropical Trees and Shrubs. *Journal of Biogeography*, *3*(3), 231. https://doi.org/10.2307/3038013

Panda, S., Bhardwaj, D. R., Sharma, P., Handa, A. K., & Kumar, D. (2021). Impact of climatic patterns on phenophase and growth of multi-purpose trees of north-western mid-Himalayan ecosystem. *Trees, Forests and People*, *6*, 100143. https://doi.org/10.1016/j.tfp.2021.100143

Prasad, S. N., & Hegde, M. (1986). Phenology and seasonality in the tropical deciduous forest of Bandipur, South India. *Proceedings / Indian Academy of Sciences*, *96*(2), 121–133. https://doi.org/10.1007/BF03053328

Raju R. (2014). *Master Plan of Bannerghatta Biological Park, Bangalore* [Master Plan 2014-15 to 2033-34]. Karnataka Forest Department.

Rathcke, B., & Lacey, E. P. (1985). Phenological Patterns of Terrestrial Plants. *Annual Review of Ecology and Systematics*, *16*(1), 179–214. https://doi.org/10.1146/annurev.es.16.110185.001143

Renner, S. S., & Zohner, C. M. (2018). Climate Change and Phenological Mismatch in Trophic Interactions Among Plants, Insects, and Vertebrates. *Annual Review of Ecology, Evolution, and Systematics*, *49*(1), 165–182. https://doi.org/10.1146/annurev-ecolsys-110617-062535

Saha, D., & Sundriyal, R. (2010). Stand structure, phenology and fruit yield of Illicium griffithii in western Arunachal Pradesh, North-East India. *Indian Journal of Forestry*, *33*(4), 475–488. https://doi.org/10.54207/bsmps1000-2010-K45G7Z

Singh P & Negi G C S. (2016). Impact of climate change on phenological responses of major forest trees of Kumaun Himalaya. *ENVIS Bulletin Himalayan Ecology*, *24*, 117–121.

Soibam Lanabir Singh & U. K. Sahoo. (2019). Shift in Phenology of Some Dominant Tree species due to Climate Change in Mizoram, North-East India. *Indian Journal of Ecology*, *46*(1), 132–136.

Suhaida, M., Haron, N., Chua, L., & Chung, R. (2018). Floral Phenology and Pollination biology of Vateria Yeechongii (Dipterocarpaceae). *Journal of Tropical Forest Science*, *30*(4), 497–508. JSTOR.

Sundarapandian, S. M, Chandrasekaran, S, & Swamy, P. S. (2005). Phenological behaviour of selected tree species in tropical forests at Kodayar in the Western Ghats, Tamil Nadu, India. *Current Science*, *88*(5), 805–810.

Surajit Ghosh, Subrata Nandy, Srutisudha Mohanty, Rupesh Subba, & S.P.S. Kushwaha. (2019). Are phenological variations in natural teak (Tectona grandis) forests of India governed by rainfall? A remote sensing based investigation. *Environmental Monitoring and Assessment*, *191*(S3), 786. https://doi.org/10.1007/s10661-019-7680-0

Suresh H S & Nanda A. (2021). Comparative Phenologies of Two Tropical Dry Forests in Southern India. *Journal of Global Ecology and Environment*, *13*(1), 36–57.

Suresh, H. S., & Sukumar, R. (2018). Phenology of Ficus spp. In a tropical dry forest, Mudumalai, south India. *Journal of Forestry Research*, *29*(4), 1129–1138. https://doi.org/10.1007/s11676-017-0513-5

Van Schaik, C. P. (1986). Phenological changes in a Sumatran rain forest. *Journal of Tropical Ecology*, *2*(4), 327–347. https://doi.org/10.1017/S0266467400000973

van Schaik, C. P., Terborgh, J. W., & Wright, S. J. (1993). The Phenology of Tropical Forests: Adaptive Significance and Consequences for Primary Consumers. *Annual Review of Ecology and Systematics*, *24*(1), 353–377. https://doi.org/10.1146/annurev.es.24.110193.002033

Veríssimo, D., MacMillan, D. C., Smith, R. J., Crees, J., & Davies, Z. G. (2014). Has Climate Change Taken Prominence over Biodiversity Conservation? *BioScience*, *64*(7), 625–629. https://doi.org/10.1093/biosci/biu079

Wright, S. J., & van Schaik, C. P. (1994). Light and the Phenology of Tropical Trees. *The American Naturalist*, *143*(1), 192–199. https://doi.org/10.1086/285600

Zhen Wang, Xin Li, Junxu Xu, Zhen Yang, & Yongchun Zhang. (2021). Effects of ambient temperature on flower initiation and flowering in saffron (Crocus sativus L.). *Scientia Horticulturae*, *279*, 109859. https://doi.org/10.1016/j.scienta.2020.109859

Supplementary Data

Spearman's correlations of phenophases and weather parameters

LEAFING			
Weather parameters	**Corresponding months (df=21)**	**One-month lag (df=20)**	**Two-months lag (df=19)**
Phenophase: No leaves or Leafless (LF1)			
Total rainfall (mm)	rs=-0.584, p=.004	rs=-0.651, p=.001	rs=-0.467, p=.038
Number of rainy days (days)	rs=-0.705, p<.001	rs=-0.801, p<.001	rs=-0.632, p=.003
Soil moisture (%)	rs=-0.639, p=0.001	rs=-0.615, p=.003	rs=-0.355, p=.125
Maximum temperature (°C)	rs=0.625, p=0.002	rs=0.421, p=.057	rs=0.077, p=.747
Minimum temperature (°C)	rs=-0.357, p=0.103	rs=-0.589, p=.005	rs=-0.593, p=.006
Humidity (%)	rs=-0.405, p=0.062	rs=-0.355, p=.115	rs=-0.038, p=.875
Sunshine (hours)	rs=0.116, p=0.606	rs=-0.312, p=.169	rs=-0.617, p=.004
Phenophase: Leaf initiation (LF2)			
Total rainfall (mm)	rs=-0.042, p=.851	rs=-0.428, p=.053	rs=-0.768, p<.001
Number of rainy days (days)	rs=-0.113, p=.617	rs=-0.463, p=.034	rs=-0.775, p<.001
Soil moisture (%)	rs=-0.232, p=.299	rs=-0.575, p=.006	rs=-0.883, p<.001
Maximum temperature (°C)	rs=0.524, p=.012	rs=0.614, p=.003	rs=0.334, p=.150
Minimum temperature (°C)	rs=0.387, p=.075	rs=0.007, p=.975	rs=-0.276, p=.238
Humidity (%)	rs=-0.268, p=.228	rs=-0.565, p=.008	rs=-0.544, p=.013
Sunshine (hours)	rs=0.552, p=.008	rs=0.409, p=.065	rs=0.133, p=.576
Phenophase: Leaf elongation (LF3)			
Total rainfall (mm)	rs=0.092, p=.068	rs=-0.148, p=.521	rs=-0.428, p=.06
Number of rainy days (days)	rs=0.162, p=.471	rs=-0.217, p=.345	rs=-0.529, p=.016
Soil moisture (%)	rs=-0.042, p=.856	rs=-0.300, p=.186	rs=-0.623, p=.003
Maximum temperature (°C)	rs=0.392, p=.071	rs=0.522, p=.0152	rs=0.540, p=.014
Minimum temperature (°C)	rs=0.558, p=0.007	rs=0.328, p=.147	rs=-0.054, p=.820
Humidity (%)	rs=-0.012, p=0.956	rs=-0.395, p=.076	rs=-0.613, p=.004
Sunshine (hours)	rs=0.551, p=0.008	rs=0.623, p=.003	rs=0.398, p=.082
Phenophase: Mature leaves (LF4)			
Total rainfall (mm)	rs=0.543, p=.009	rs=0.687, p<.001	rs=0.594, p=.006
Number of rainy days (days)	rs=0.625, p=.002	rs=0.805, p<.001	rs=0.778, p<.001
Soil moisture (%)	rs=0.588, p=.004	rs=0.695, p<.001	rs= 0.6, p=.005
Maximum temperature (°C)	rs=-0.652, p=.001	rs=-0.261, p=.098	rs=-0.191, p=.419
Minimum temperature (°C)	rs=0.093, p=.68	rs=0.440, p=.046	rs=0.542, p=.014
Humidity (%)	rs=0.400, p=.065	rs=0.435, p=.049	rs=0.325, p=.162
Sunshine (hours)	rs=-0.280, p=.207	rs=0.061, p=.793	rs=0.314, p=.178
Phenophase: Senescing (falling) leaves (LF5)			
Total rainfall (mm)	rs=-0.623, p=.002	rs=-0.389, p=.081	rs=-0.047, p=.845
Number of rainy days (days)	rs=-0.773, p<.001	rs=-0.502, p=.020	rs=-0.063, p=.793
Soil moisture (%)	rs=-0.569, p=.006	rs=-0.244, p=.286	rs=0.182, p=.443
Maximum temperature (°C)	rs=0.308, p=.162	rs=-0.265, p=.245	rs=-0.54, p=.014
Minimum temperature (°C)	rs=-0.500, p=.018	rs=-0.608, p=.003	rs=-0.469, p=.037
Humidity (%)	rs=-0.546, p=.009	rs=-0.074, p=.75	rs=0.311, p=.182
Sunshine (hours)	rs=-0.194, p=.386	rs=-0.632, p=.002	rs=-0.723, p<.001
FLOWERING			
Weather parameters	**Corresponding months (df=21)**	**One-month lag (df=20)**	**Two-months lag (df=19)**
Phenophase: No flowers or flowerless (FL1)			
Total rainfall (mm)	rs=-0.033, p=.882	rs=0.356, p=.113	rs=0.689, p<.001
Number of rainy days (days)	rs=-0.051, p=.821	rs=0.358, p=.111	rs=0.767, p<.001
Soil moisture (%)	rs=0.172, p=.443	rs=0.552, p=.009	rs=0.85, p<.001
Maximum temperature (°C)	rs=-0.471, p=.027	rs=-0.621, p=.003	rs=-0.57, p=.008
Minimum temperature (°C)	rs=-0.468, p=.028	rs=-0.173, p=.454	rs=0.170, p=.472
Humidity (%)	rs=0.171, p=.446	rs=0.569, p=.007	rs=0.695, p<.001
Sunshine (hours)	rs=-0.601, p=.003	rs=-0.648, p=.001	rs=-0.327, p<.16

Phenophase: Flower initiation (FL2)			
Total rainfall (mm)	rs=-0.198, p=.376	rs=-0.573, p=.006	rs=-0.767, p<.001
Number of rainy days (days)	rs=-0.276, p=.214	rs=-0.599, p=.004	rs=-0.875, p<.001
Soil moisture (%)	rs=-0.362, p=.098	rs=-0.716, p<.001	rs=-0.870, p<.001
Maximum temperature (°C)	rs=0.586, p=.004	rs=0.612, p=.003	rs=0.349, p=.131
Minimum temperature (°C)	rs=0.250, p=.262	rs=-0.140, p=.544	rs=-0.406, p=.076
Humidity (%)	rs=-0.312, p=.158	rs=-0.592, p=.005	rs=-0.591, p=.006
Sunshine (hours)	rs=0.547, p=.008	rs=0.309, p=.173	rs=0.067, p=.779
Phenophase: Flower opening (FL3)			
Total rainfall (mm)	rs=-0.144, p=.522	rs=-0.467, p=.033	rs=-0.641, p=.002
Number of rainy days (days)	rs=-0.082, p=.716	rs=-0.543, p=.011	rs=-0.757, p<.001
Soil moisture (%)	rs=-0.328, p=.136	rs=-0.657, p=.001	rs=-0.795, p<.001
Maximum temperature (°C)	rs=0.461, p=.031	rs=0.711, p<.001	rs=0.497, p=.026
Minimum temperature (°C)	rs=0.373, p=.087	rs=0.106, p=.648	rs=-0.261, p=.266
Humidity (%)	rs=-0.189, p=.399	rs=-0.629, p=.002	rs=-0.68, p=.001
Sunshine (hours)	rs=0.575, p=.005	rs=0.547, p=.010	rs=0.305, p=.192
Phenophase: Mature or pollinated flowers (FL4)			
Total rainfall (mm)	rs=0.247, p=.267	rs=-0.216, p=.347	rs=-0.528, p=.017
Number of rainy days (days)	rs=0.307, p=.164	rs=-0.171, p=.458	rs=-0.576, p=.008
Soil moisture (%)	rs=0.071, p=.755	rs=-0.347, p=.124	rs=-0.647, p=.002
Maximum temperature (°C)	rs=0.303, p=.171	rs=0.622, p=.003	rs=0.649, p=.002
Minimum temperature (°C)	rs=0.394, p=.069	rs=0.268, p=.238	rs=-0.009, p=.967
Humidity (%)	rs=0.161, p=.474	rs=-0.353, p=.116	rs=-0.465, p=.039
Sunshine (hours)	rs=0.267, p=.230	rs=0.564, p=.008	rs=0.339, p=.143
Phenophase: Senescing (falling) flowers (FL5)			
Total rainfall (mm)	rs=-0.071, p=.755	rs=-0.482, p=.027	rs=-0.540, p=.014
Number of rainy days (days)	rs=0.105, p=.643	rs=-0.347, p=.124	rs=-0.689, p=.001
Soil moisture (%)	rs=-0.231, p=.301	rs=-0.589, p=.005	rs=-0.707, p<.001
Maximum temperature (°C)	rs=0.389, p=.074	rs=0.526, p=.014	rs=0.599, p=.005
Minimum temperature (°C)	rs=0.353, p=.107	rs=0.102, p=.660	rs=-0.044, p=.855
Humidity (%)	rs=-0.255, p=.253	rs=-0.623, p=.003	rs=-0.594, p=.006
Sunshine (hours)	rs=0.565, p=.006	rs=0.675, p=.001	rs=0.288, p=.218
FRUITING			
Weather parameters	**Corresponding months (df=21)**	**One-month lag (df=20)**	**Two-months lag (df=19)**
Phenophase: No fruits or fruitless (FR1)			
Total rainfall (mm)	rs=-0.502, p=.017	rs=-0.423, p=.056	rs=-0.296, p=0204
Number of rainy days (days)	rs=-0.592, p=.003	rs=-0.539, p=.012	rs=-0.488, p=.029
Soil moisture (%)	rs=-0.541, p=.009	rs=-0.445, p=.043	rs=-0.225, p=.341
Maximum temperature (°C)	rs=0.472, p=0.026	rs=0.236, p=.302	rs=0.246, p=.296
Minimum temperature (°C)	rs=-0.097, p=.668	rs=-0.427, p=.054	rs=-0.353, p=.127
Humidity (%)	rs=-0.327, p=.137	rs=-0.235, p=.305	rs=-0.161, p=.497
Sunshine (hours)	rs=0.332, p=.130	rs=0.008, p=.971	rs=-0.353, p=.126
Phenophase: Fruit initiation (FR2)			
Total rainfall (mm)	rs=0.013, p=.954	rs=-0.246, p=.283	rs=-0.137, p=.565
Number of rainy days (days)	rs=0.134, p=.553	rs=-0.195, p=.397	rs=-0.439, p=.053
Soil moisture (%)	rs=-0.038, p=.863	rs=-0.269, p=.239	rs=-0.377, p=.101
Maximum temperature (°C)	rs=0.334, p=.128	rs=0.679, p=.001	rs=0.622, p=.003
Minimum temperature (°C)	rs=0.363, p=.097	rs=0.299, p=.188	rs=0.223, p=.345
Humidity (%)	rs=0.128, p=.569	rs=-0.201, p=.382	rs=-0.349, p=.132
Sunshine (hours)	rs=0.318, p=.149	rs=0.550, p=.010	rs=0.391, p=.088
Phenophase: Fruit elongation (FR3)			
Total rainfall (mm)	rs=0.405, p=.061	rs=0.104, p=.654	rs=-0.194, p=.412
Number of rainy days (days)	rs=0.579, p=.005	rs=0.244, p=.287	rs=-0.229, p=.330
Soil moisture (%)	rs=0.272, p=.221	rs=-0.105, p=.650	rs=-0.421, p=.064
Maximum temperature (°C)	rs=-0.106, p=.637	rs=0.404, p=.069	rs=0.546, p=.013
Minimum temperature (°C)	rs=0.497, p=.018	rs=0.574, p=.007	rs=0.417, p=.067
Humidity (%)	rs=0.208, p=.353	rs=-0.281, p=.218	rs=-0.562, p=.010

Sunshine (hours)	rs=0.352, p=.108	rs-=.757, p<.001	rs=0.771, p=<.001
Phenophase: Mature fruits (FR4)			
Total rainfall (mm)	rs=0.659, p<.001	rs=0.748, p<.001	rs=0.533, p=.015
Number of rainy days (days)	rs=0.673, p<.001	rs=0.854, p<.001	rs=0.552, p=.001
Soil moisture (%)	rs=0.824, p=.001	rs=0.806, p<.001	rs=0.463, p=.040
Maximum temperature (°C)	rs=-0.697, p<.001	rs=-0.538, p=.012	rs=-0.185, p=.436
Minimum temperature (°C)	rs=0.232, p=.298	rs=0.502, p=.020	rs=0.493, p=.027
Humidity (%)	rs=0.693, p<.001	rs=0.632, p=.002	rs=0.265, p=.259
Sunshine (hours)	rs=-0.498, p=.018	rs=-0.011, p=.962	rs=0.465, p=.039
Phenophase: Senescing (falling) fruits (FR5)			
Total rainfall (mm)	rs=-0.687, p<.001	rs=-0.623, p=.003	rs=-0.364, p=.115
Number of rainy days (days)	rs=-0.74, p<.001	rs=-0.813, p<.001	rs=-0.495, p=.026
Soil moisture (%)	rs=-0.714, p<.001	rs=-0.610, p=.003	rs=-0.328, p=.158
Maximum temperature (°C)	rs=0.650, p=.001	rs=0.210, p=.360	rs=-0.174, p=.463
Minimum temperature (°C)	rs=-0.018, p=.936	rs=-0.299, p=.187	rs=-0.409, p=.074
Humidity (%)	rs=-0.655, p<.001	rs=-0.421, p=.058	rs=-0.168, p=.478
Sunshine (hours)	rs=0.296, p=.181	rs=-0.036, p=.876	rs=-0.344, p=.138

Multiple regressions of PC1, PC2, and PC3 with phenophases

Details	**Leaf initiation**			**Flower initiation**			**Fruit elongation**		
Dependent variable	**LF2**	**LF2T1**	**LF2T2**	**FL2**	**FL2T1**	**FL2T2**	**FR3**	**FR3T1**	**FR3T2**
Observations N:	22	21	20	22	21	20	22	21	20
Multiple R:	0.716	0.639	0.687	0.638	0.751	0.866	0.576	0.752	0.803
Multiple R^2:	0.513	0.409	0.472	0.407	0.564	0.750	0.331	0.566	0.644
Multiple R^2 adj.:	0.432	0.304	0.373	0.308	0.487	0.703	0.220	0.489	0.577
F-value	6.326	3.918	4.760	4.119	7.327	15.978	2.975	7.392	9.652
p-value	0.004	0.027	0.015	0.022	0.002	0.000	0.059	0.002	0.001
Variance inflation factor (VIF)	2.054	1.691	1.893	1.687	2.293	3.996	1.496	2.304	2.810

Phenophase		**Parameters**	**Intercept (constant)**	**PC1**	**PC2**	**PC3**
Leaf initiation	Corresponding month (LF2)	Coefficient	12.008	-2.307	2.891	2.963
		p-value	0.000	0.003	0.009	0.118
	One-month lag (LF2T1)	Coefficient	11.426	-2.641	0.417	0.869
		p-value	0.000	0.004	0.736	0.680
	Two-months lag (LF2T2)	Coefficient	11.288	-1.685	-2.718	0.246
		p-value	0.000	0.040	0.036	0.904
Flower initiation	Corresponding month (FL2)	Coefficient	20.038	-2.804	2.943	3.335
		p-value	0.000	0.008	0.048	0.208
	One-month lag (FL2T1)	Coefficient	19.641	-3.877	0.300	2.833
		p-value	0.000	0.000	0.824	0.229
	Two-months lag (FL2T2)	Coefficient	19.578	-3.081	-3.620	1.242
		p-value	0.000	0.000	0.003	0.488
Fruit elongation	Corresponding month (FR	Coefficient	12.310	1.001	2.176	-4.062
		p-value	0.000	0.255	0.102	0.098
	One-month lag (FR3T1)	Coefficient	12.199	-1.932	4.538	-0.180
		p-value	0.000	0.014	0.001	0.924
	Two-month lag (FR3T2)	Coefficient	11.765	-3.055	3.149	1.080
		p-value	0.000	0.000	0.005	0.520