ISSN (Online): 2349-1183; ISSN (Print): 2349-9265
TROPICAL PLANT RESEARCH
The Journal of the Society for Tropical Plant Research
11(2): 46–57, 2024
DOI: 10.22271/tpr.2024.v11.i2.008

Research article

Phenological patterns of woody plant species in a tropical dry forest, Bannerghatta National Park, Bengaluru, India

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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, Bengaluru, India. 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 (rs = 0.524, $p<0.05$ for leaf initiation; rs = 0.586, $p<0.05$ for flower initiation) and sunshine hours (rs = 0.552, $p<0.01$ for leaf initiation; rs = 0.546, $p<0.05$ for flower initiation). Leaf and flower initiations were highly correlated and significant (rs=0.926, $p<.001$). Principal Component Analysis (PCA) 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 - Tropical dry deciduous forests - Bannerghatta - Principal Component Analysis.

[Cite as: Sharma B, Kumar VGA, Poorvashree P, Kumar KHV, Begum N, Saha D & Suresh HS (2024) Phenological patterns of woody plant species in a tropical dry forest, Bannerghatta National Park, Bengaluru, India. *Tropical Plant Research* 11(2): 46–57]

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 (Opler *et al*. 1976, Bendix *et al*. 2006, Bajpai *et al*. 2017, Bao *et al.* 2021, Barrett & Brown 2021), temperature (Caroline & Fernandez 1993, Jagadish *et al*. 2016, Devi *et al*. 2019,

Received: 20 March 2024
Published: 31 August 2024
https://doi.org/10.22271/tpr.2024.v11.i2.008

Meng *et al*. 2020), and photoperiod (vanSchaik 1986, Wright & vanSchaik 1994, Borchert & Rivera, 2001; Adole *et al*. 2019) - lead to an alteration in the timing of leafing, flowering, and fruiting. Biotic factors (ultimate causes) such as herbivory (Collinge & Louda 1989, Aide 1993, Murali & Sukumar 1993, vanSchaik *et al*. 1993, Meineke *et al*. 2021) and pollinators (Gentry 1974, Appanah 1993, Forrest 2015, 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, Bajpai *et al*. 2015, Singh & Sahoo 2019, Woldearegay 2020). 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 & Negi 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 changing climate scenario, community-level phenological monitoring becomes all the more important, either using remote sensing technology (Ayushi *et al.* 2022) or through periodic field visits to understand the variations in phenophases.

Rainfall-related events govern tropical forest phenology. Leaf phenology in evergreen and deciduous forests is dependent on regional rainfall patterns (Saha & Sundriyal 2010, Hannah 2011, Bajpai *et al*. 2012, Nanda 2013, Aravind *et al*. 2013, Ghosh *et al*. 2019). Temperatures do affect plant growth, with warmer temperatures increasing the rate of phenological development (Hatfield & Prueger 2015, Barrett & Brown 2021). The onset of flowering and peak flowering in most forest types are implicated in the increase in temperatures (Bajpai *et al*. 2017, Mohanta *et al*. 2020, Ahmad *et al*. 2021, 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 & Nanda 2021). In addition to temperatures, photoperiod is also an important environmental cue in germination and the onset of flowering (Rathcke & Lacey 1985, Bajpai *et al*. 2017). It has been shown by 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 (Prasad & Hegde 1986, Bhat 1992, Murali & Sukumar 1993, Bhat & Murali 2001, Nanda *et al.* 2011). 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 Bannerghatta National Park (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 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 Bannerghatta National Park (BNP). BNP has an area of 260.51 km^2. BNP is surrounded by Bengaluru 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 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 mean 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 (Fig. 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* (Roxb. Ex DC.) Wall. ex Guill. & Perr., *Polyalthia cerasoides* (Roxb.) Bedd., *Acacia chundra* (Roxb. ex Rottler) Willd., *Terminalia bellirica* (Gaertn.) Roxb., *Strychnos potatorum* L.f., *Terminalia paniculata* B.Heyne ex Roth, and *Buchanania axillaris* (Desr.) Ramamoorthy. The common understorey species include *Ixora arborea* Roxb. ex Sm., *Erythroxylum monogynum* Roxb., *Maytenus emarginata* (Willd.) Ding Hou, *Phyllanthus polyphyllus* Willd., *Grewia orbiculata* Rottler, *Bauhinia racemosa* Lam., *Cassia fistula* L., *Holarrhena antidysenterica* (Roth) A.DC., *Ochna obtusata* DC., and *Canthium parviflorum* Lam. In addition to the canopy and understorey species, woody climbers and stragglers such as *Ventilago madraspatana* Gaertn., *Hiptage benghalensis* (L.) Kurz, *Ziziphus oenoplia* (L.) Mill., *Acacia pennata* (L.) Willd., *Mimosa rubicaulis* Lam., *Pterolobium hexapetalum* (Roth) Santapau & Wagh, all form part of the vegetation. Invasive species such as *Chromolaena odorata* (L.) R.M.King & H.Rob and *Lantana camara* L. 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 developed by the 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)

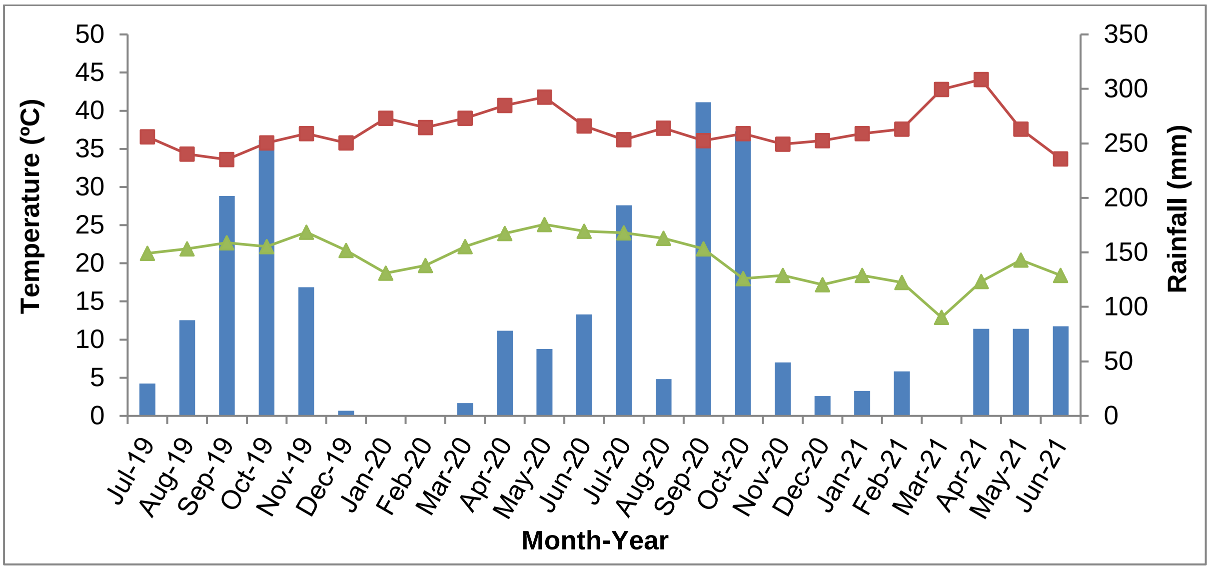

Figure 1. Total monthly rainfall (mm) and mean monthly maximum (■), mean monthly minimum (▲) temperature (^{0}C) during July 2019 to June 2021 at Bannerghatta National Park, Bengaluru, India.

RESULTS

Community patterns of phenology

i. Vegetative phenology: The leafless stage started in the month of November and reached its maximum in the early part of the March month (Fig. 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 (Fig. 2).

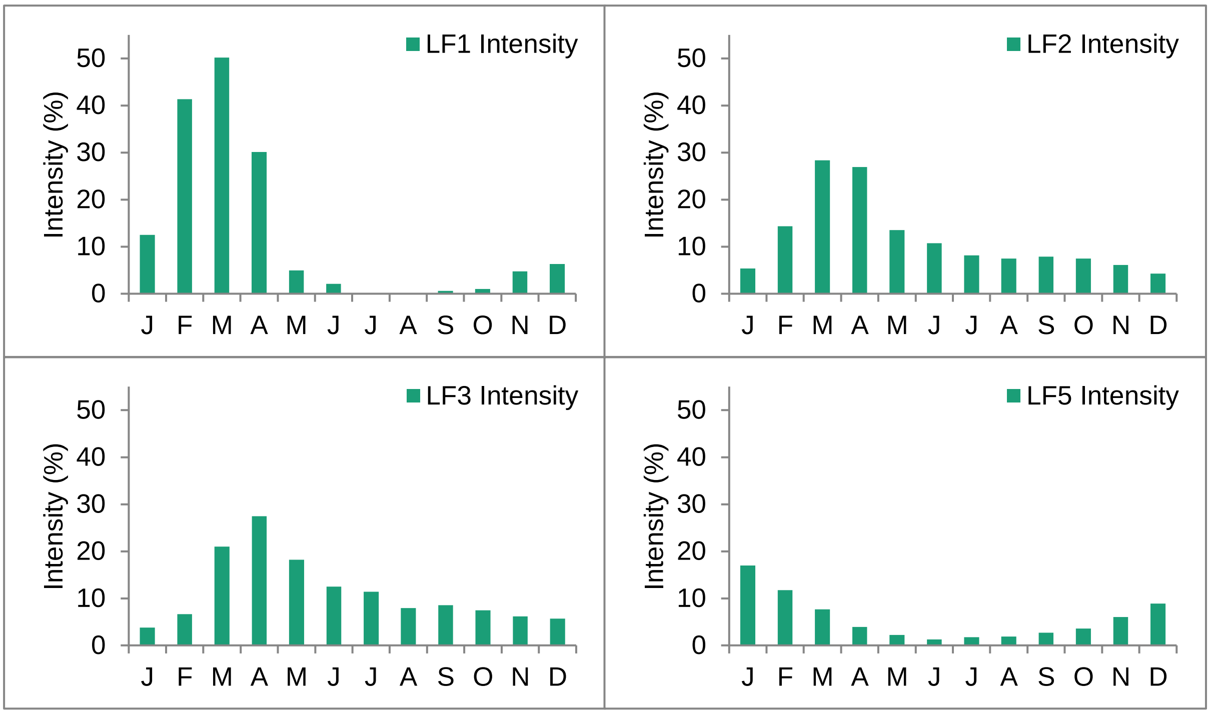

Figure 2. Leafless stage (LF1), Leaf initiation (LF2), Leaf elongation (LF3) & Leaf senescence (LF5) in Bannerghatta National Park, Bengaluru, India.

ii. 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 (Fig. 3).

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 (Fig. 4).

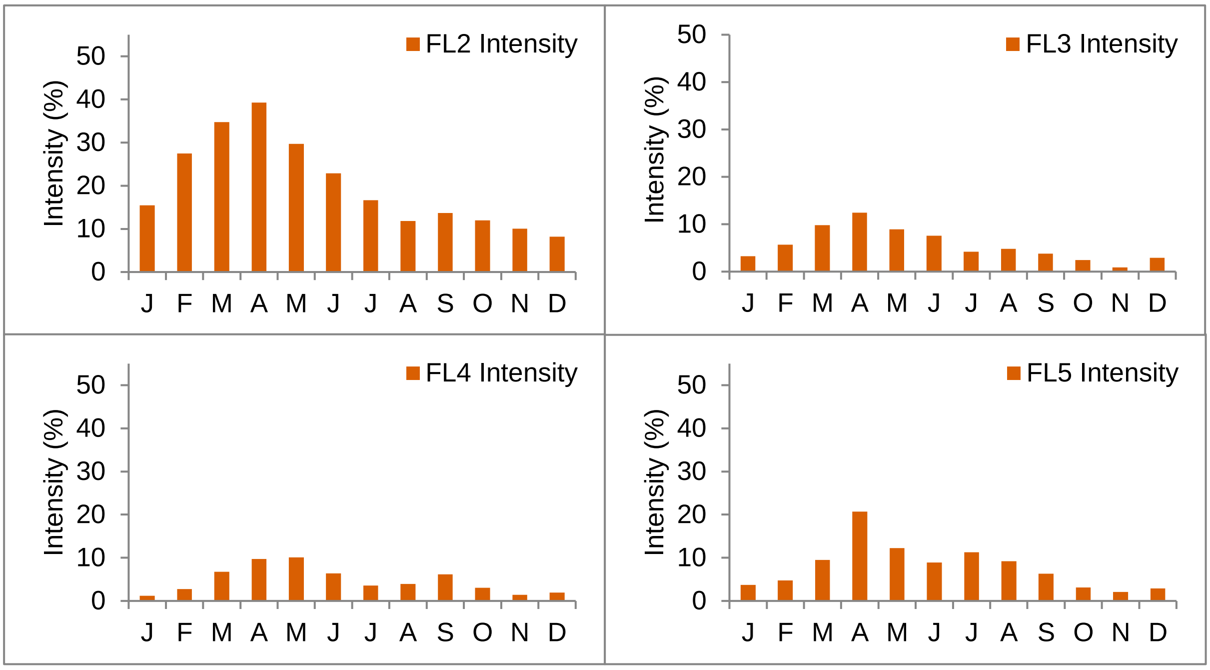

Figure 3. Flower initiation (FL2), Flower opening (FL3), Flower maturation (FL4) & Flower dehiscence (FL5) in Bannerghatta National Park, Bengaluru, India.

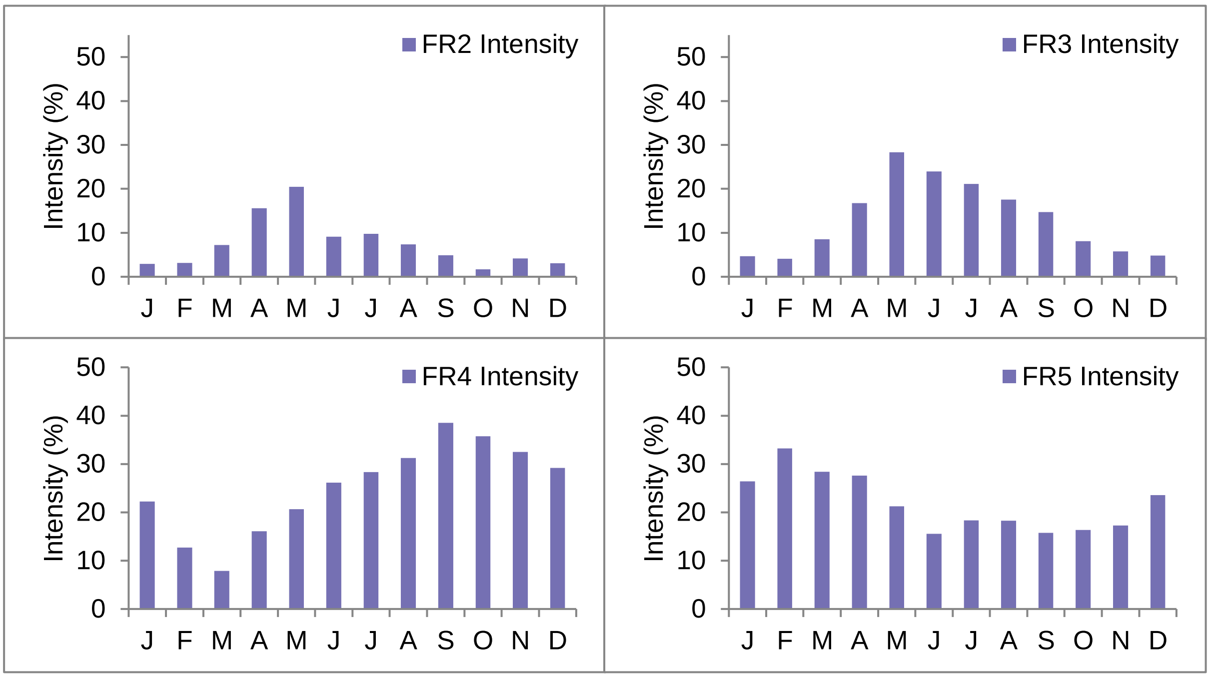

Figure 4. Fruit initiation (FR2), fruit elongation (FR3), fruit maturation (FR4) & fruit dehiscence (FR5) in Bannerghatta National Park, Bengaluru, India.

Factors influencing phenology

i. 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).

b) 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.

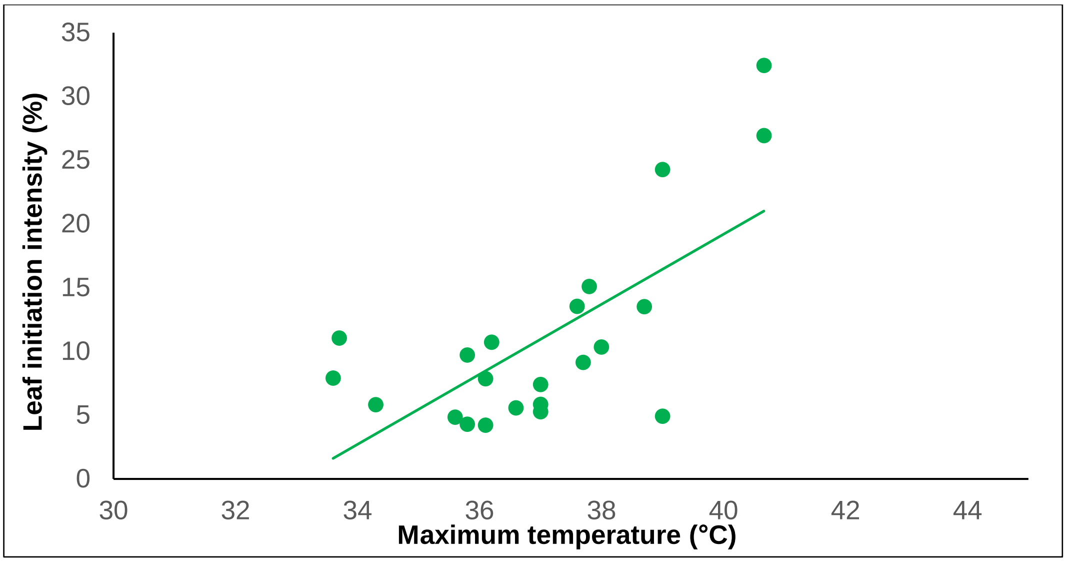

Figure 5. Intensity of leaf initiation (LF2) in relation to maximum temperature in Bannerghatta National Park, Bengaluru, India.

ii. 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) (Fig. 6).

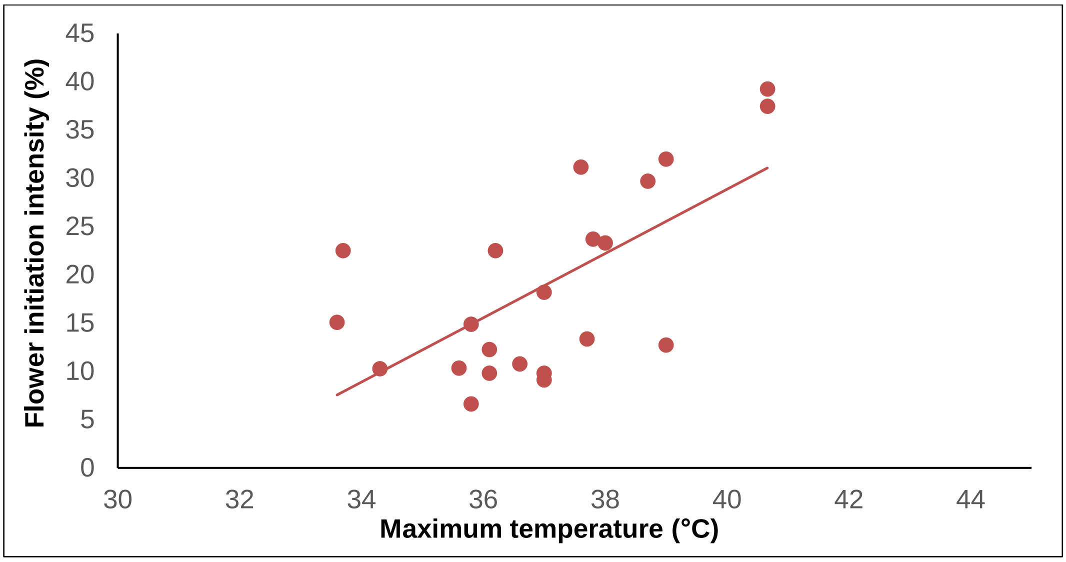

Figure 6. Flower initiating intensity (FL2) in relation to maximum temperature in Bannerghatta National Park, Bengaluru, India.

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

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

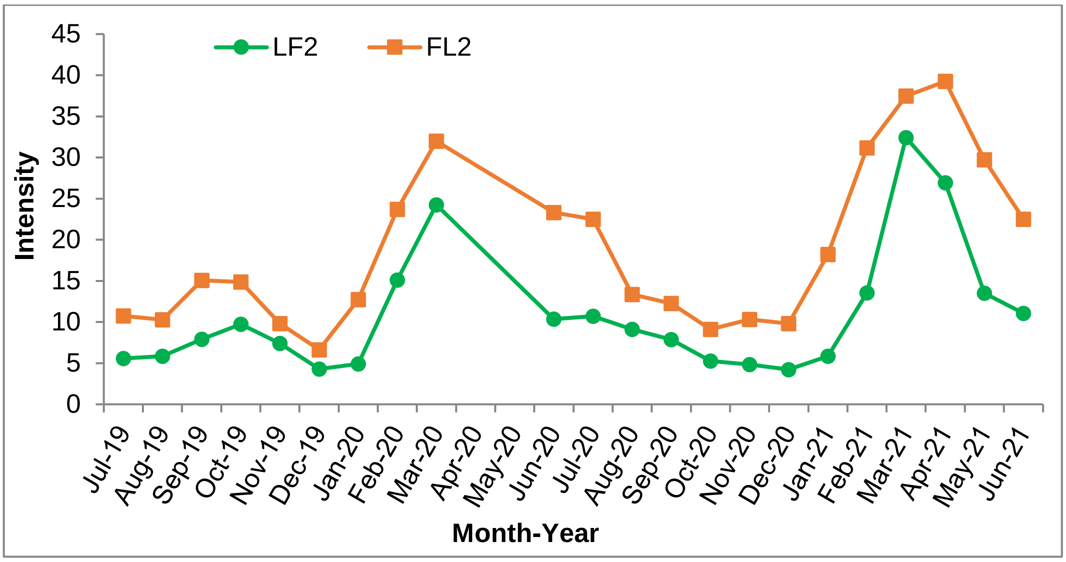

Figure 7. Intensities of leaf initiation (LF2) versus flower initiation (FL2) (broader base of peaks during 2020 is due to the absence of observations during the months of April & May 2020)

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

i. *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.

ii. *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.

a) 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).

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

b) 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).

c) 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 (Prasad & Hegde 1986, Elliott *et al*. 2006, Nanda *et al*. 2020).

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 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 & Yadava 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 2013; Nanda *et al*. 2015) in the Western Ghats and in the subtropics (Devi *et al*. 2019, Kikim & Yadava 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 *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 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 & Yadava 2001, Sundarapandian *et al*. 2005, Nanda *et al*. 2011) 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 *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 *et al.* (2005) in the Kodayar forests of the Western Ghats.

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.

CONCLUSION

The current study underpins 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.

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