CHAPTER 4
PHENOLOGY

Objective II: To assess the impacts of meteorological parameters on the phenophases of plants through extensive field visits.

4.1 Introduction

The spatiotemporal patterns of vegetation phenophases in the Himalayan region are governed by several factors like topography, climate, vegetation type, resource availability, etc. [1,2]. However, scientists recognize plant phenophases as prominent responses to alterations in climatic variables – precipitation, temperature, insolation, as well as relative humidity [3,4]. When the Southwest Asian monsoon hits the Indian subcontinent, it causes a distinct seasonal change in the weather that affects the occurrences of both vegetative and reproductive phenophases [5]. This is due to the fact that in the Indian subcontinent, the phenophases associated with plant greening begin with the onset of the summer monsoon, which itself is characterised by significant changes in precipitation and temperature [2].

Field and experimental studies have frequently highlighted that although phenophases display plasticity in terms of timings and durations, their patterns of occurrences of phenophases are species-specific responses to the environmental factors [6,7]. Despite the widely recognized association between phenophases of trees in tropical forests and climate, the occurrences and durations of phenophases are highly diverse [8]. According to Reich [9], the variation in the phenophases' onsets in tropical trees signify the presence of definitive physiological responses to climatic variables. Similarly, Lalruatfela and Tripathi [10] suggested that the intrinsic qualities of tropical trees govern the variations in deciduousness duration in response to unfavourable conditions. Several studies have shown that in the tropical regions with distinct seasonality, the climatic variables acting as cues for phenophases tend to vary [11]. Studies conducted in seasonal forests revealed that in the dry season, the forests usually received an increase of 25-50% in photosynthetically active radiation (PAR), whereas during the rainy season, PAR was 20-30% less [11,12]. Therefore, in the absence of clear seasonal variations in temperature, the availability of water and light predominantly governs the occurrences of several phenophases like leaf initiation, leaf fall and so on [11,13]. Conversely, distinct seasonal variations in temperature often report both temperature and precipitation as cues for vegetative phenophases [8,14]. Changes in temperature and irradiance are considered to trigger the occurrence of leaf initiation and the resulting leaf flush, prior to the occurrence of monsoon [2,11,15]. As phenophases are species-specific responses to the climate, deciduous trees lose their leaves before or after rainy season as a way to adapt to cooler temperature or less water availability, while evergreen trees retain their leaves throughout all seasons [16,17,18,19]. However, for reproductive phenophases like flowering, which is similar to leaf initiation, the most commonly reported climatic variables as cues are solar irradiance and temperature [8,20]. Different weather conditions can cause vegetative and reproductive phenophases to happen at different times. These phenophases are evolutionary responses of species to abiotic environment that helps the reproductive and vegetative parts gets the optimal resources that are available [15,21].

The Southwest monsoon causes the climate in the northeastern part of India to shift from tropical to subtropical conditions, resulting in different seasons and a combination of deciduous coupled with evergreen species at lower altitudes [22]. The presence of evergreen species along with deciduous species in the forests of Northeast India imparts characteristic phenological patterns that is distinctive from those observed in the dry deciduous, and evergreen forests of other parts of India [13]. Initial phenological research conducted in this region by Boojh and Ramakrishnan [23] and Shukla and Ramakrishnan [24] showed that the phenological patterns resembled those of Indian dry forests [22]. Several phenological researches have been carried out in different parts of Northeast India's Eastern Himalayas in the last two decades. Most of them found that temperature and precipitation were the predominant indicators for phenophases [2,25,26,27]. However, a few studies have also reported other climatic variables like photoperiod and relative humidity as cues for phenophases [22,28]. As these studies are sporadic, it has resulted in limited understanding of the association of climatic parameters like, temperature, precipitation, relative humidity, and photosynthetically active radiation with phenophases of tree species of the tropical semi-evergreen forests of Eastern Himalayan foothill region. This study was conducted to comprehensively address the research gap.

4.2 Methodology

4.2.1 Phenological data

Ten different tree species were selected within Sonai Rupai Wildlife Sanctuary, namely *Bauhinia purpurea*, *Bombax ceiba*, *Dillenia indica*, *Gmelina arborea*, *Lagerostroemia speciosa*, *Magnolia hodgsonii*, *Sterculia villosa*, *Tectona grandis*, *Tetrameles nudiflora* and

Toona ciliata, which characterized the tropical semi-evergreen forests and were dominant in the protected area (Fig. 4.1). For each tree species, 5 replicates (Table 4.1) were selected through random sampling without replacement ensuring that among the replicates of a particular tree species the diameter at breast height (DBH) varied by no more than ± 5 cm and their geographic coordinates were noted [29]. The study was carried out for 2 years from October 2021 to September 2023. The phenological data for the 9 phenophases, namely leaf initiation, leafing, leaf fall, flower initiation, flowering, flower fall, fruit initiation, fruiting and fruit fall were recorded through visual observations during the second week of each month. The presence and absence of each of the selected phenophases were noted for all the replicates of each selected species. For a particular individual tree, if two or more phenophases were observed at the same time, all the observed phenophases were recorded. If a single individual of all the replicates of a species displayed a phenophase, it signified that the environmental conditions were conducive for the species, whereas the exhibition of phenophase by all the replicates signified optimal conditions. Therefore, a species was considered to display the phenophase if it was observed on at least one of its replicates. The formation of leaf buds marked the leaf initiation stage. The leafing stage was differentiated from the leaf initiation stage (formation of leaf buds) by observing the development of distinct leaves and the subsequent change in leaf colour. Whereas the stage of leaf fall is characterized by transition in leaf colour to a brown or yellow shade, leading to leaf abscission. The flower initiation stage consisted of the unopened flower buds, and the flowering stage was recorded from the opening of flower buds until the occurrence of flower fall, i.e. the shedding of flowers from the plant. The stage of fruit initiation is defined by the transformation of the ovary into the defined shape of the fruit. The fruiting stage refers to the period that spans from the formation of the distinguishable shape of the fruit up to its maturation stage. This is followed by the fruit fall stage, marked by the abscission of the fruits.

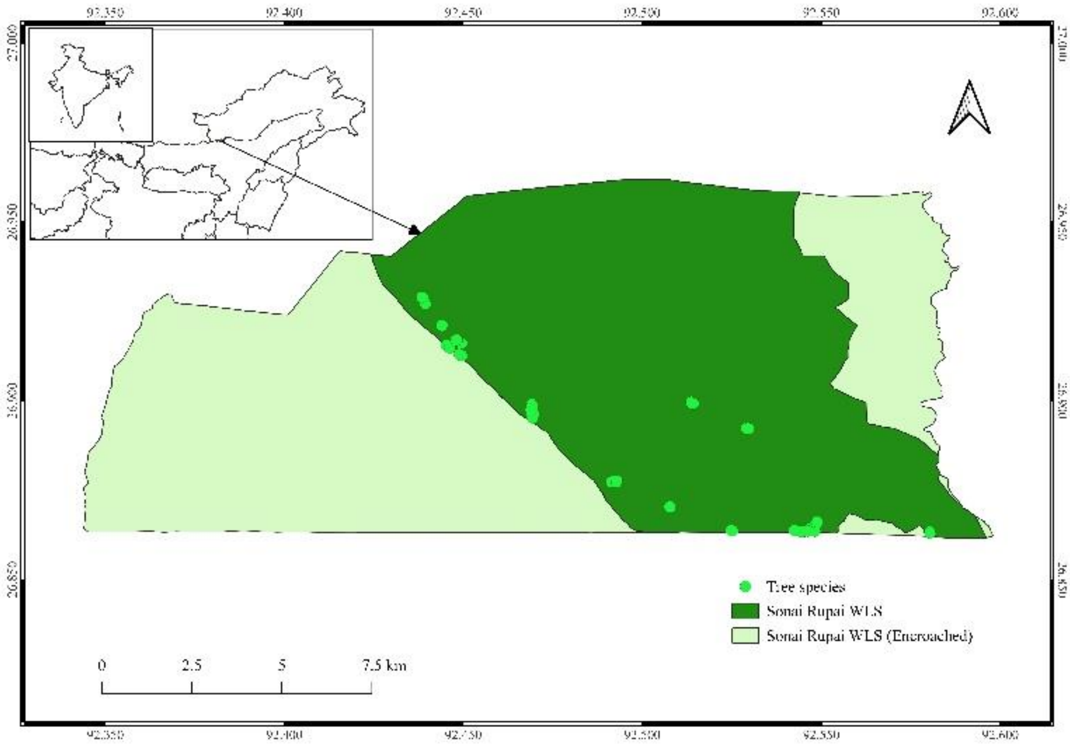

Fig. 4.1: Map displaying the location of the tree species along with the replicates within the study site

Table 4.1. Ten selected different tree species along with their replicates' DBH (m) and coordinates for detail phenological study at Sonai Rupai Wildlife Sanctuary of Assam

Tree species	Type	Replicate 1	Replicate 2	Replicate 3	Replicate 4	Replicate 5.
Bauhinia purpurea	Evergreen	0.12 m 26°54'55.86" N 92°26'42.83" E	0.14 m 26°54'53.30" N 92°26'46.43" E	0.16m 26°54'45.49" N 92°26'58.36" E	0.15 m 26°53'44.30" N 92°28'10.00" E	0.15 m 26°51'48.98" N 92°51'48.98" E
Bombax ceiba	Deciduous	0.36 m 26°51'50.59" N 92°32'46.86" E	0.34 m 26°51'55.05" N 92°32'53.89" E	0.32 m 26°51'55.15" N 92°32'54.31" E	0.34 m 26°51'49.33" N 92°31'30.56" E	0.39 m 26°51'49.36" N 92°31'29.46" E
Dillenia indica	Evergreen	0.41 m 26°52'38.34" N 92°29'29.31" E	0.42 m 26°53'58.73" N 92°30'49.26" E	0.38 m 26°53'57.25" N 92°30'51.06" E	0.44 m 26°53'56.29" N 92°28'09.12" E	0.46 m 26°53'55.19" N 92°28'09.48" E
Gmelina arborea	Deciduous	0.19 m 26°53'32.03" N 92°31'46.73" E	0.22 m 26°53'32.29" N 92°31'45.07" E	0.20 m 26°53'32.13" N 92°31'46.40" E	0.17 m 26°53'43.73" N 92°28'09.08" E	0.21 m 26°55'00.84" N 92°26'53.23" E
Lagerstroemia speciosa	Deciduous	0.43 m 26°51'49.66" N 92°32'50.75" E	0.45 m 26°51'50.23" N 92°32'51.90" E	0.41 m 26°51'48.88" N 92°32'53.52" E	0.43 m 26°51'48.75" N 92°32'38.42" E	0.48 m 26°51'48.66" N 92°32'42.78" E
Magnolia hodgsonii	Evergreen	0.17 m 26°55'37.44" N 92°26'21.82" E	0.19 m 26°53'47.62" N 92°28'10.21" E	0.22 m 26°52'38.49" N 92°29'34.23" E	0.19 m 26°52'39.08" N 92°29'34.36" E	0.20 m 26°51'58.22" N 92°32'55.88" E
Sterculia villosa	Deciduous	0.44 m 26°54'46.96" N 92°26'56.17" E	0.42 m 26°54'57.84" N 92°26'58.09" E	0.47 m 26°55'00.70" N 92°26'53.76" E	0.45 m 26°55'00.68" N 92°26'52.91" E	0.46 m 26°55'01.40" N 92°26'52.75" E

Tectona grandis	Deciduous	0.38 m 26°51’50.00” N 92°32’46.62” E	0.43 m 26°51’50.06” N 92°32’45.42” E	0.40 m 26°51’48.83” N 92°32’42.84” E	0.39 m 26°51’48.77” N 92°32’42.11” E	0.34 m 26°51’48.80” N 92°32’42.29” E
Tetrameles nudiflora	Deciduous	0.97 m 26°51’48.93” N 92°32’46.62” E	1.01 m 26°51’49.79” N 92°32’32.80” E	0.92 m 26°53’42.83” N 92°28’09.70” E	0.99 m 26°55’01.19” N 92°26’53.50” E	0.94 m 26°53’50.53” N 92°28’08.13” E
Toona ciliata	Evergreen	0.32 m 26°52’13.20” N 92°30’27.76” E	0.36 m 26°51’47.22” N 92°34’49.35” E	0.29 m 26°51’47.92” N 92°34’49.05” E	0.34 m 26°55’44.19” N 92°26’18.71” E	0.36 m 26°55’15.83” N 92°26’38.53” E

4.2.2 Meteorological data

The meteorological data for the study site was acquired from the Prediction of Worldwide Energy Resource (POWER) Project at the Langley Research Center (LaRC) of the National Aeronautics and Space Administration (NASA). This study considered the climatic parameters of mean air temperature, precipitation amount, mean relative humidity (RH) and mean photosynthetically active radiation (PAR) for each month of the study period.

4.2.3 Data analysis

The species were considered to be displaying a particular phenophase if at least one of the replicates displayed that specific phenophase. The number of replicates for each species as well as the total number of species displaying any of the phenophases were recorded. Spearman's rank correlation analysis was performed both at the species level and overall using SPSS 26.0 to determine the coefficient between the selected climatic parameters and phenophases [25]. The correlations of the phenophases with the climatic variables were considered significant when $p \leq 0.05$. To analyze the annual phenophase events for each species and overall, circular statistical analysis was used with Rayleigh's test for uniformity at a significance level of $p \leq 0.05$ in Oriana. These tests were aimed to assess the even distribution of the observed phenophases over the study period. The phenological data of the overall were graphed in circular plots, using a circular or y-axis of 10 units to represent the total number of tree species considered for the phenological study. Since the phenological data were recorded monthly for two years, dividing the angular or x-axis into 12 segments of 30°, each segment represented a month from January to December. MS Excel 2021 and Oriana were used for data tabulation and generation of graphical representations.

4.3 Results

4.3.1 Meteorological data

During the study period 2021-2023, monthly fluctuations were observed in the climatic variables (Table 4.2). The precipitation (rainfall) ranged between 0 mm to 579.51 mm. The lowest precipitation (0 mm) was recorded in November 2022 while the highest precipitation was recorded in July 2022 signifying the occurrence of the Southwest monsoon. The monthly mean of temperature ranged from 11.2 °C, recorded in February 2022, to 25.15 °C, recorded in July 2023. The relative humidity was recorded as lowest (59.25%) in March

2022 while the highest (90.45%) was recorded in June 2022. The monthly mean of photosynthetically active radiation (PAR) was lowest (62.6 W m^{-2}) in January 2022 and highest (102.5 W m^{-2}) in May 2023. The lowest values of the climatic variable were frequently recorded during the winter and premonsoon seasons while the highest values were recorded during the late premonsoon and monsoon seasons.

Table 4.2: Monthly precipitation and monthly mean of relative humidity, temperature and photosynthetically active radiation during the period 2021-2023

Months	Precipitation (mm)	Relative Humidity (RH)	Temperature (°C)	Photosynthetically Active Radiation (W m^{-2}) PAR
October-2021	60.22	83.14	21.8	85.46
November-2021	1.28	80.22	15.97	77.2
December-2021	1.38	77.02	13.61	67.71
January-2022	18.53	76.01	11.75	62.6
February-2022	65.00	75.67	11.2	71.9
March-2022	62.35	59.25	19.54	91.47
April-2022	302.23	81.1	20.37	69.21
May-2022	346.26	82.11	22.53	83.35
June-2022	579.51	90.45	23.08	64.73
July-2022	223.39	86.11	24.79	100.7
August-2022	102.36	85.09	25.01	99.82
September-2022	104.56	86.63	23.38	86.08
October-2022	182.2	84.05	20.65	78.5
November-2022	0	74.44	16.45	84.6
December-2022	2.57	81.47	13.84	64.15
January-2023	0.10	74.69	12.18	67.2
February-2023	14.37	70.42	14.81	67.6
March-2023	55.69	69.35	17.66	78.75
April-2023	84.49	65.24	20.93	99.67
May-2023	139.15	69.73	22.76	102.5
June-2023	412.24	80.96	24.81	84.78
July-2023	215.76	83.75	25.15	93.57
August-2023	314.01	88.06	24.64	85.64
September-2023	80.88	81.75	24.51	102.01

4.3.2 Variation in monthly phenophases

The phenological study included both evergreen and deciduous trees present at the study site. The graphic representation that depicts the occurrences of phenophases of ten selected tree species during the study period (2021-2023) is presented in Fig. 4.2(a)-(j). The trees with evergreen traits like *Dillenia indica*, *Magnolia hodgsonii* and *Toona ciliata* displayed the occurrences of vegetative phenophases throughout the year. However, *Dillenia indica* and *Toona ciliata* exhibited a brief period where leaf initiation was not observed (Fig. 4.2(c) and 1(j)). The deciduous trees displayed a distinct period of deciduousness marked with the presence of leaf fall along with the absence of leaf initiation and leafing. The observation of several deciduous species, including *Bombax ceiba, Gmelina arborea, Sterculia villosa, Tectona grandis* and *Tetrameles nudiflora*, highlights the potential alignment of phenophases occurrences with the changing climatic conditions. During the study periods, it has been observed that the number of species displaying vegetative phenophases – leaf initiation, leafing, and leaf fall, declined during the period from November to May. However, from April onwards, a resurgence in leaf initiation and leafing was observed as all the tree species displayed these vegetative phenophases. For the reproductive phenophases like flowering and fruiting, a peak was observed for flowering prior to the onset of the monsoon. However, a single distinct seasonal peak was not observed for fruit initiation, fruiting, and fruit fall, but rather two small peaks were observed, i.e., one occurring in the monsoon and the other in the post-monsoon seasons (Table 4.3). *Magnolia hodgsonii* and *Tectona grandis* exhibited an extended period of fruiting for four to five months while other species varied between 1 to 3 months (Fig. 4.2(a)-(j)). *Dillenia indica* and *Lagerostroemia speciosa* display fruiting during August to October exhibiting fruit fall in during October to December. Fruiting of *Magnolia hodgsonii* occurred during July to November and fruit fall in November to December. The flowering period lasts for two months for most of the studied species but, *Dillenia indica*, *Tetrameles nudiflora* and *Toona ciliata* showed only for a month. This is because the reproductive phenophases are species-specific; the onsets and durations of these phenophases vary between species.

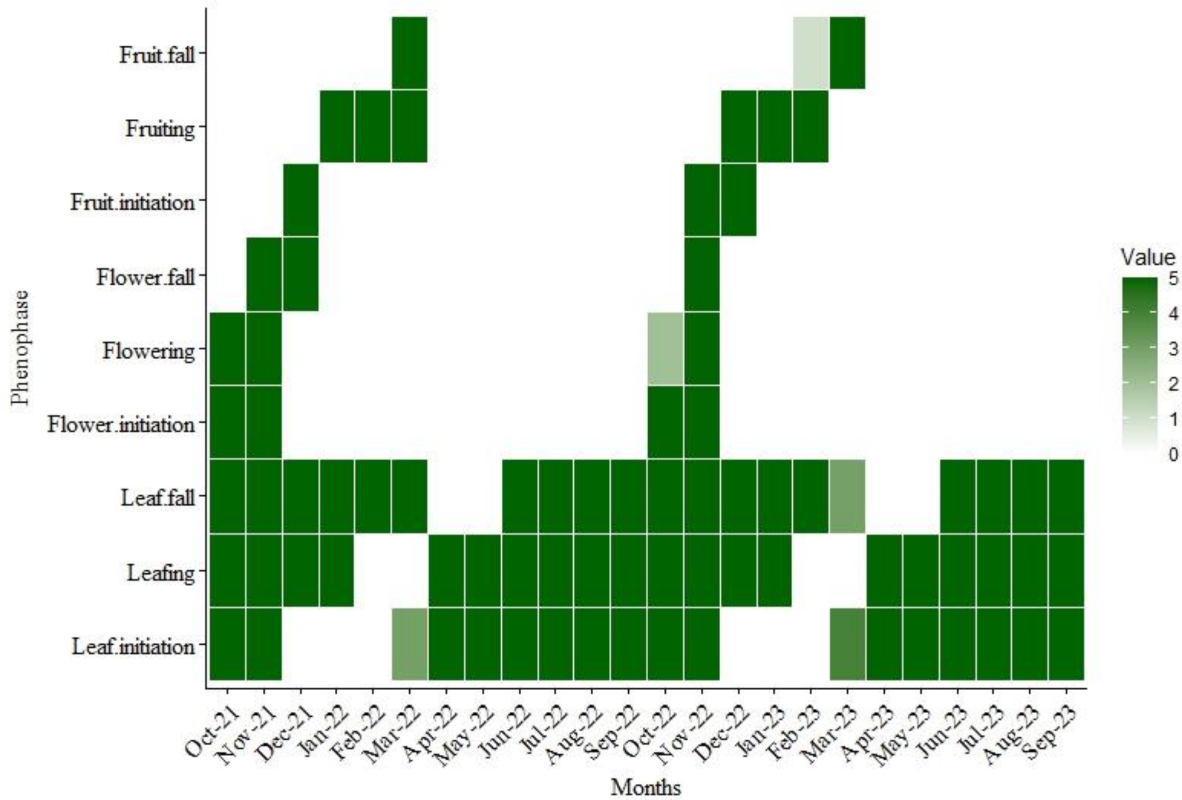

Fig. 4.2(a): Variation in monthly phenophases of *Bauhinia purpurea* during the study period (2021-2023).

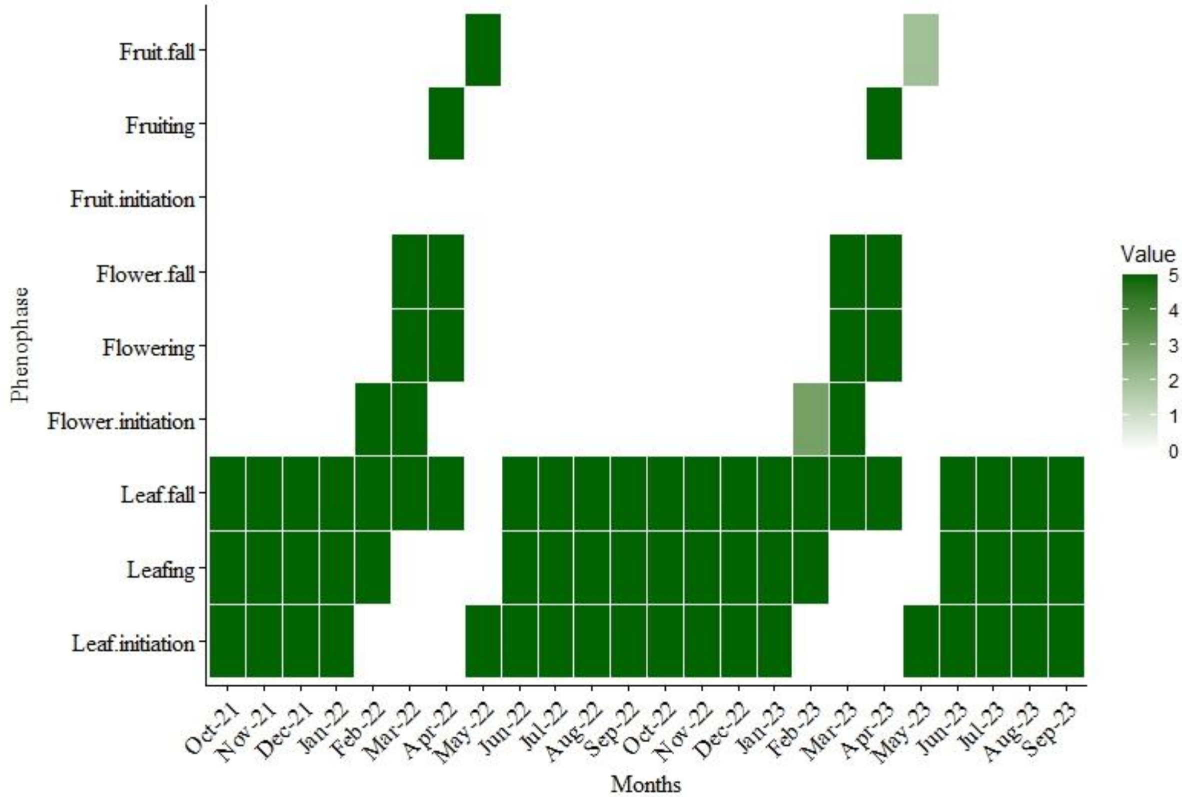

Fig. 4.2(b): Variation in monthly phenophases of *Bombax ceiba* during the study period (2021-2023).

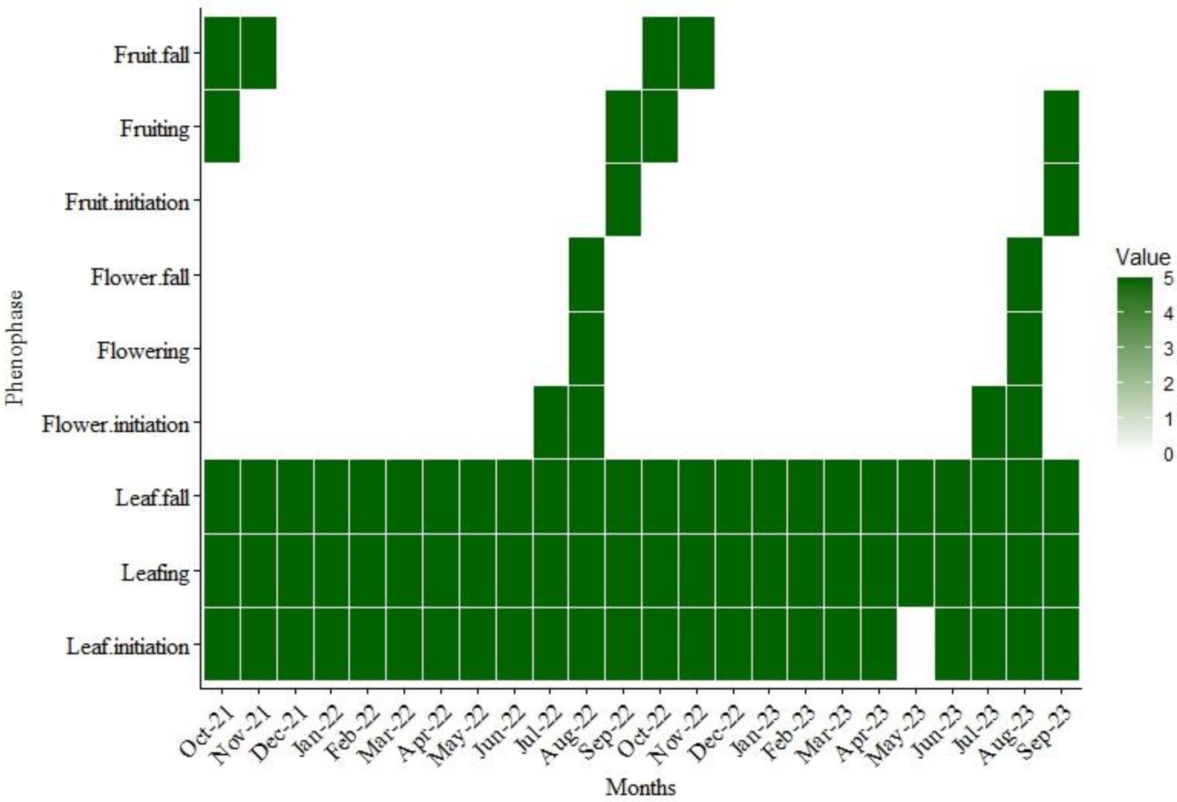

Fig. 4.2(c): Variation in monthly phenophases of *Dillenia indica* during the study period (2021-2023).

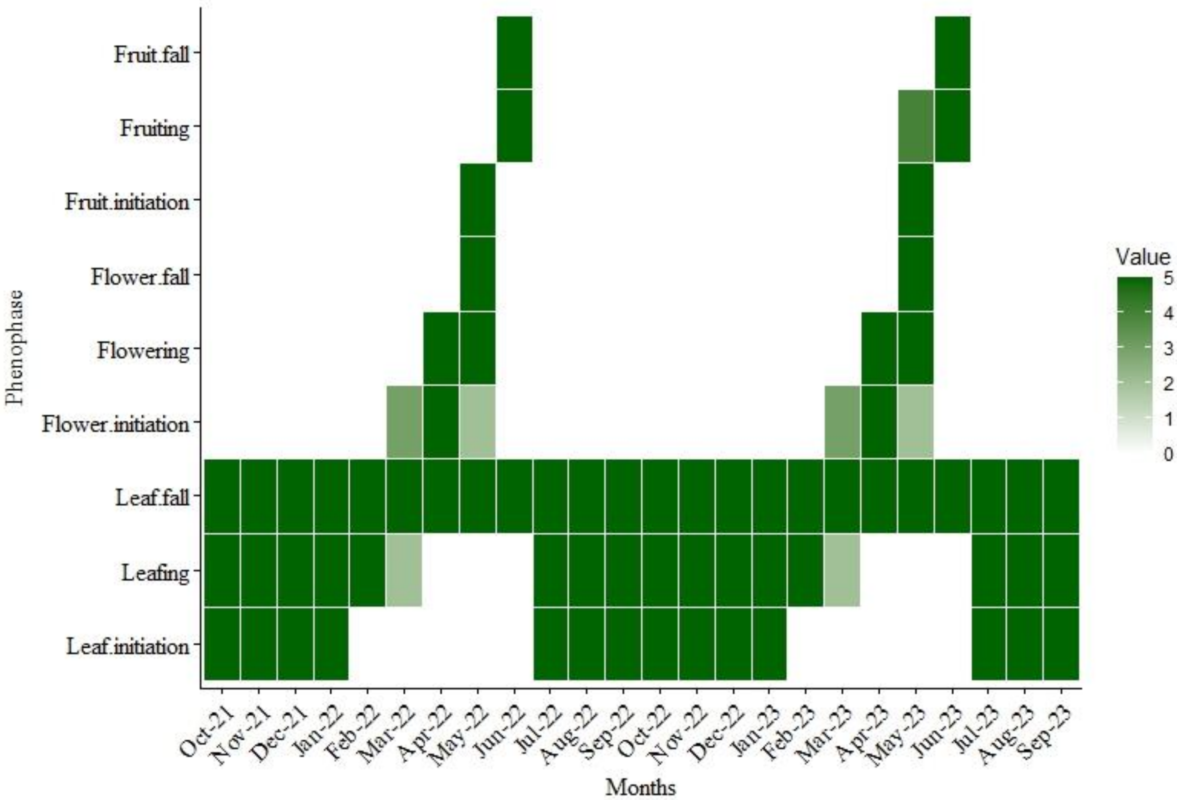

Fig. 4.2(d): Variation in monthly phenophases of *Gmelina arborea* during the study period (2021-2023).

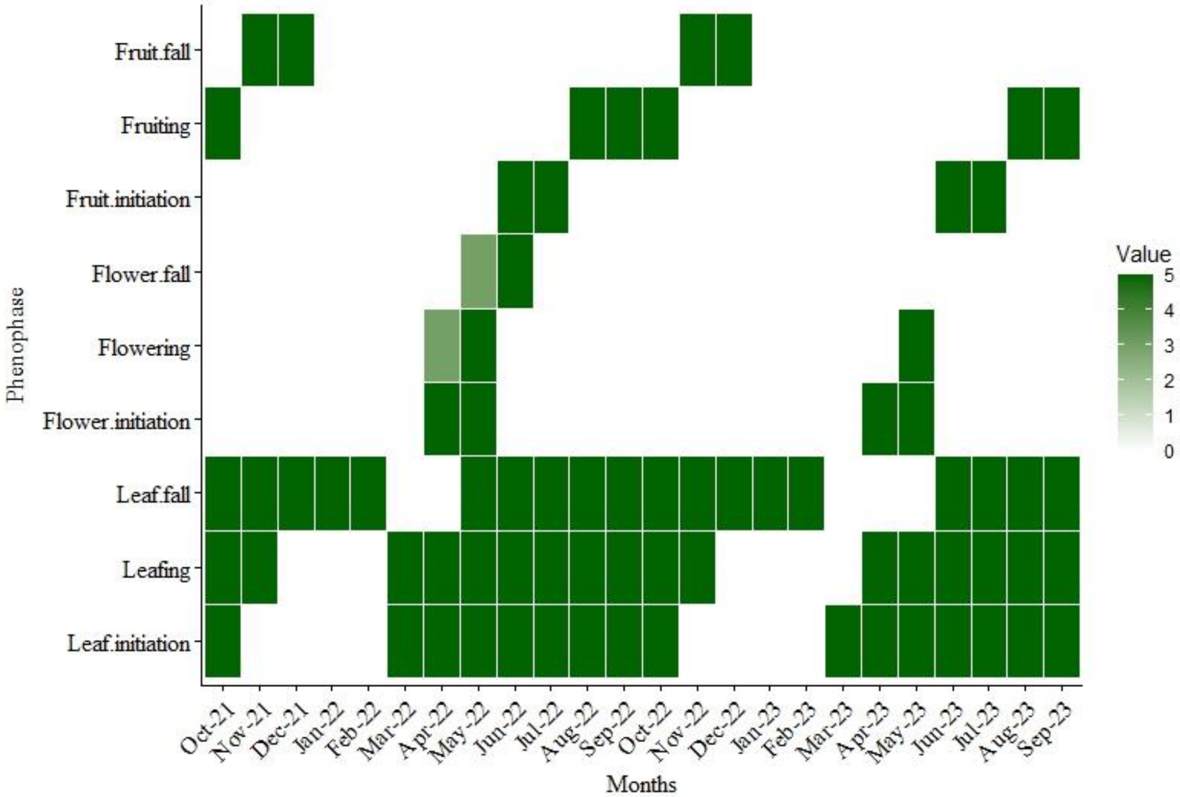

Fig. 4.2(e): Variation in monthly phenophases of *Lagerostroemia speciosa* during the study period (2021-2023).

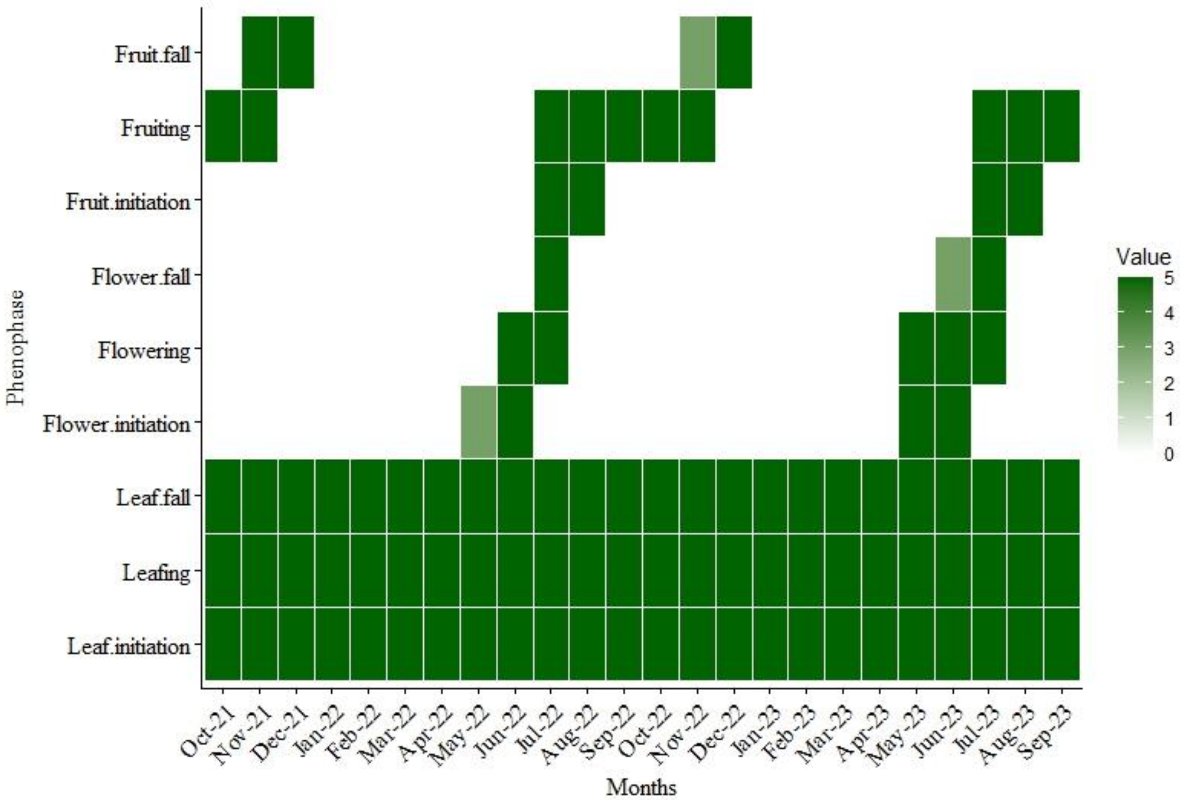

Fig. 4.2(f): Variation in monthly phenophases of *Magnolia hodgsonii* during the study period (2021-2023).

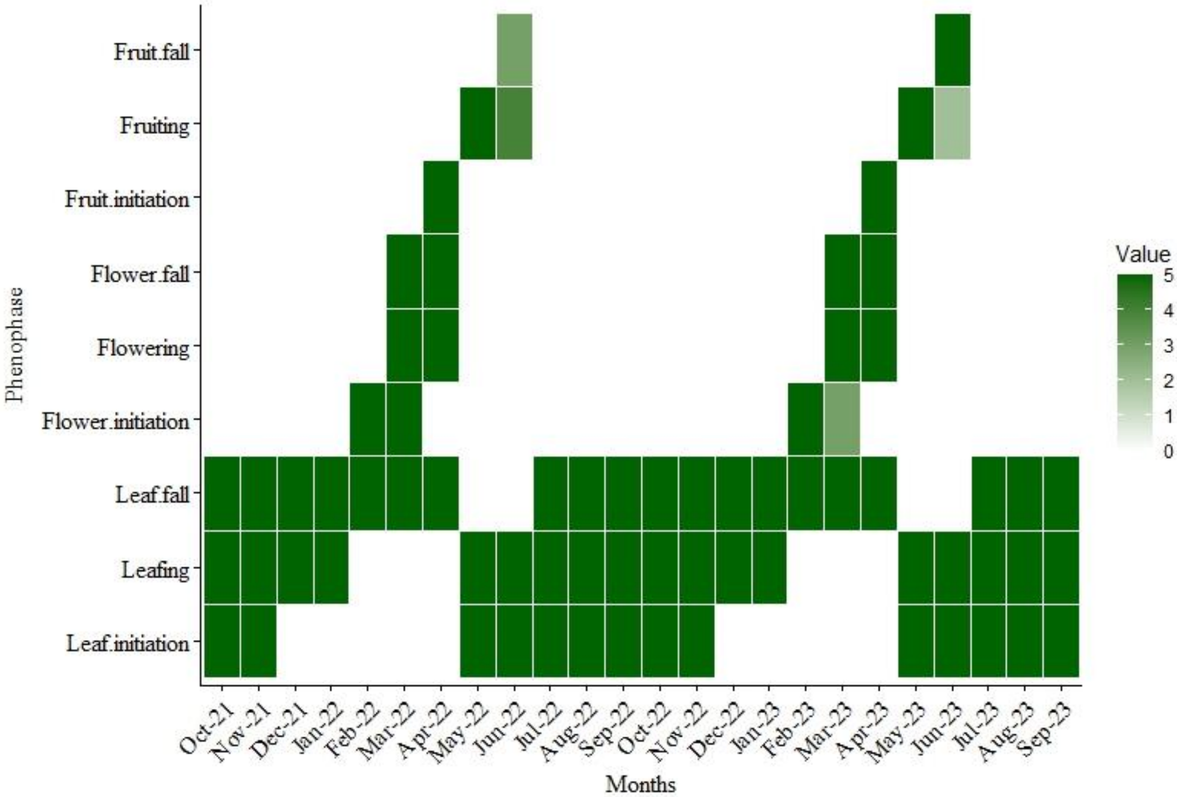

Fig. 4.2(g): Variation in monthly phenophases of *Sterculia villosa* during the study period (2021-2023).

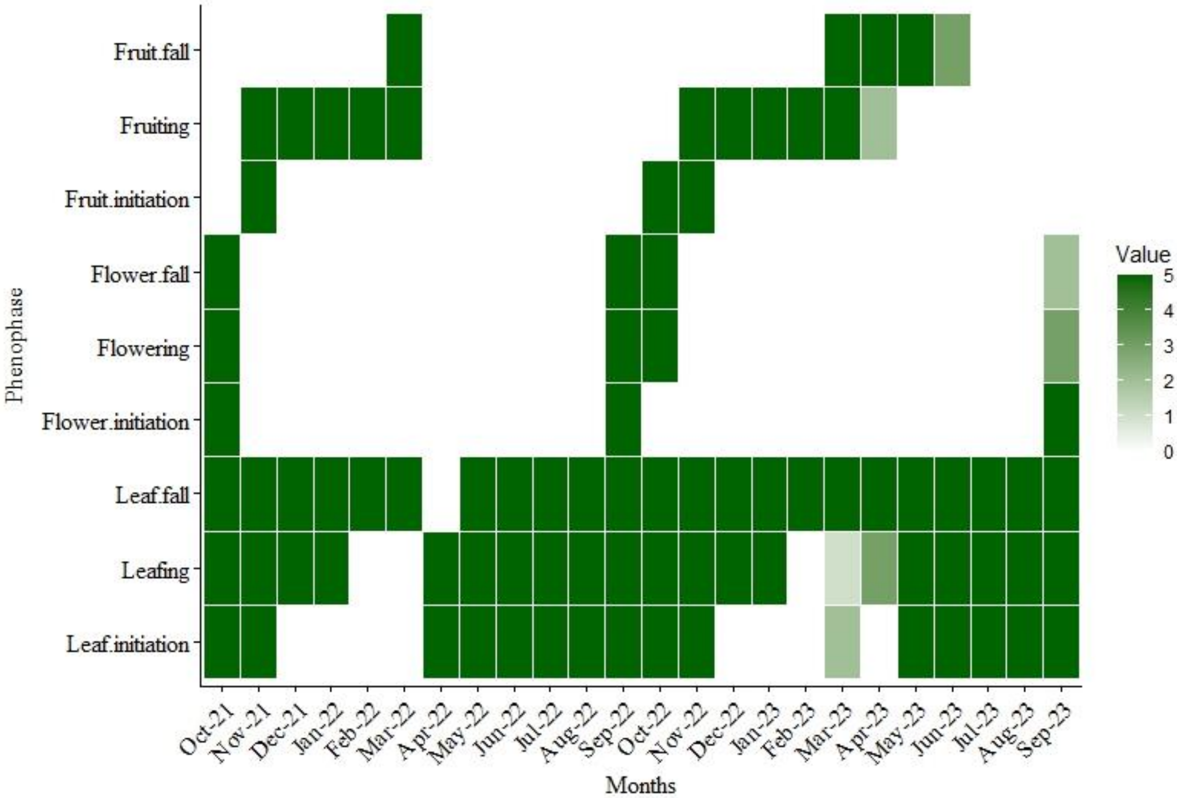

Fig. 4.2(h): Variation in monthly phenophases of *Tectona grandis* during the study period (2021-2023).

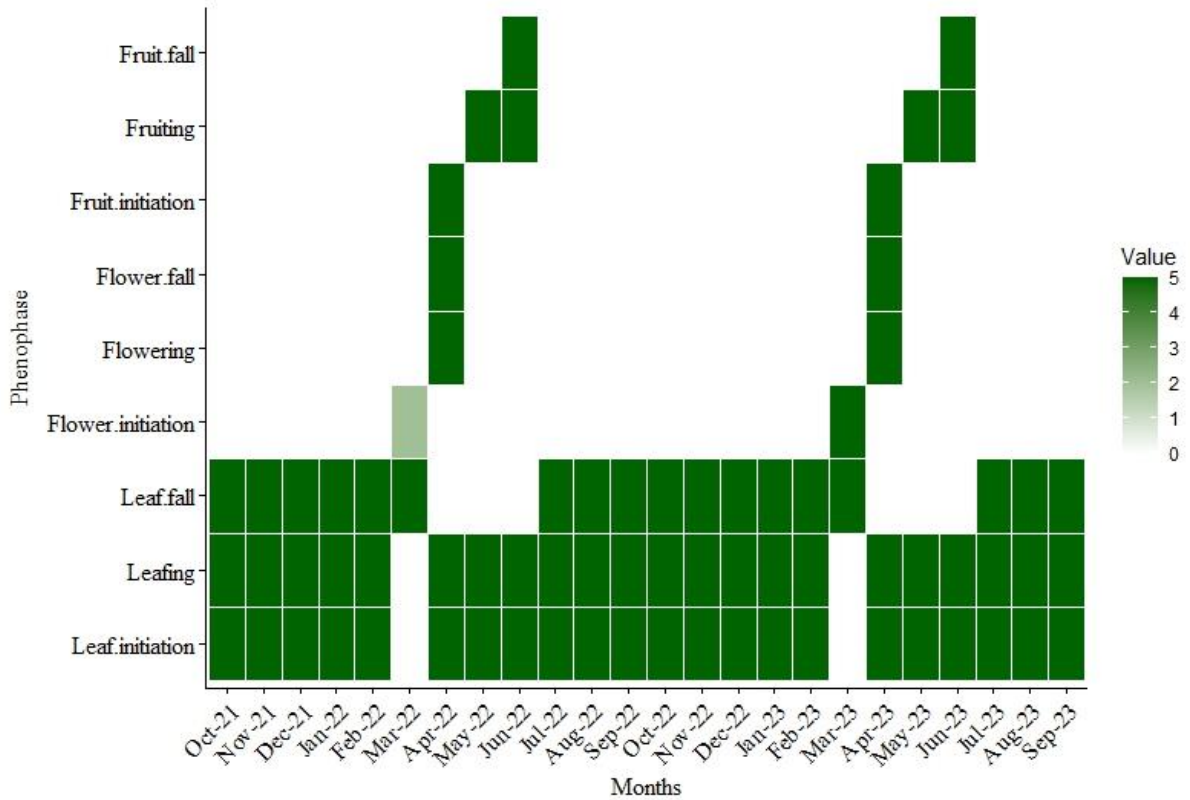

Fig. 4.2(i): Variation in monthly phenophases of *Tetrameles nudiflora* during the study period (2021-2023).

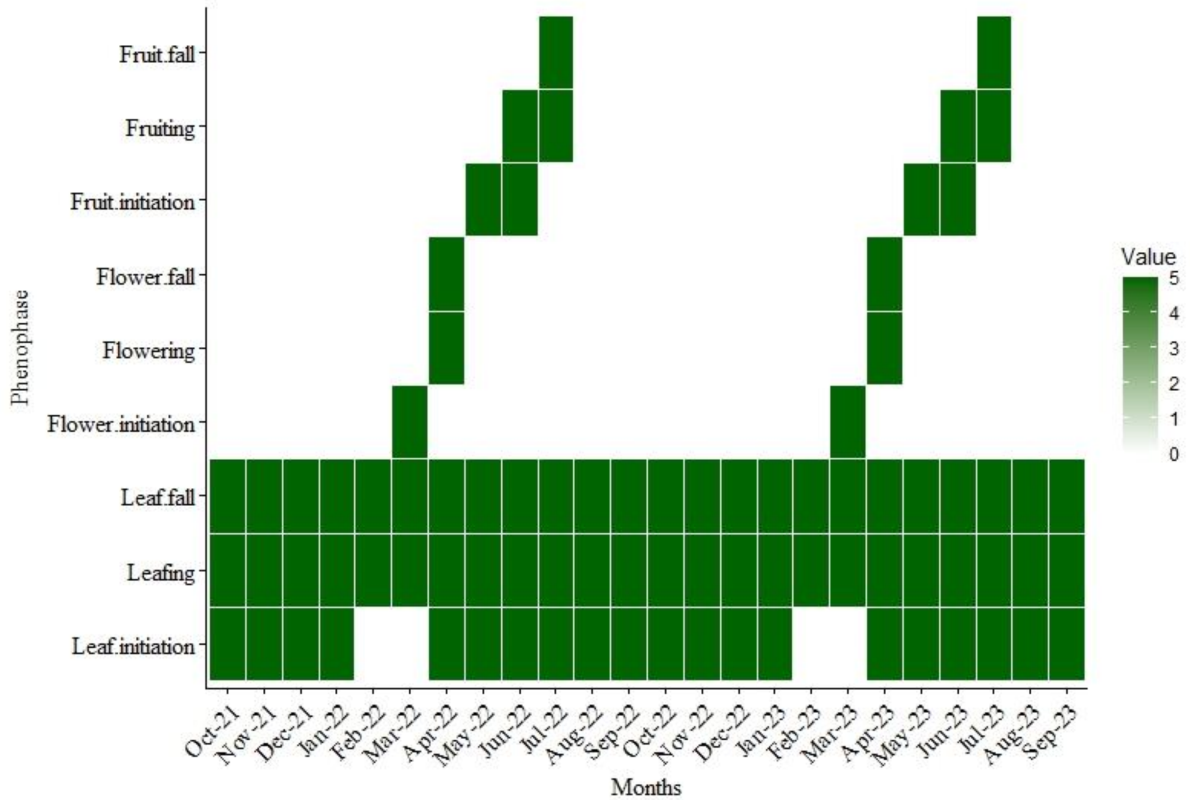

Fig. 4.2(j): Variation in monthly phenophases of *Toona ciliata* during the study period (2021-2023).

Table 4.3: Number of plant species displaying different phenophases during the study period (October 2021 – September 2023)

Phenophases	Study period: October 2021 to September 2022											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Leaf initiation	10	9	6	6	4	4	6	9	9	10	10	10
Leafing	10	10	9	9	6	5	6	8	9	10	10	10
Leaf fall	10	10	10	10	10	9	5	6	8	10	10	10
Flower initiation	2	1	0	0	2	5	3	3	1	1	1	1
Flowering	2	1	0	0	0	2	6	2	1	1	1	1
Flowering fall	1	1	0	0	0	2	4	2	1	1	1	1
Fruit initiation	0	2	1	0	0	0	1	2	2	2	1	1
Fruiting	2	2	2	2	2	2	1	2	3	2	1	3
Fruit fall	0	3	2	0	0	2	0	0	3	1	0	0
Phenophases	**Study period: October 2022 to September 2023**											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Leaf initiation	10	8	6	6	3	5	6	8	9	10	10	10
Leafing	10	10	9	9	6	5	7	8	9	10	10	10
Leaf fall	10	10	10	10	10	8	6	5	8	10	10	10
Flower initiation	1	1	0	0	2	4	2	2	1	1	1	1
Flowering	2	1	0	0	0	2	5	5	1	1	1	1
Flower fall	1	1	0	0	0	2	3	3	1	1	1	1
Fruit initiation	1	2	1	0	0	0	1	2	2	2	1	1
Fruiting	3	2	2	2	2	1	2	3	3	2	1	3
Fruit fall	1	3	2	0	1	2	1	3	4	1	0	0

4.3.3 Correlation of phenophases with climatic variables

The Spearman's rank correlation analysis revealed that leaf initiation was correlated with climatic variables such as precipitation (rs = 0.43; p = 0.03), relative humidity (rs = 0.80; p = 0.00), temperature (rs = 0.76; p = 0.00) and photosynthetically active radiation (rs = 0.52; p = 0.01) significantly. The data in Table 4.4 shows a positive correlation between leafing and relative humidity (rs = 0.68; p = 0.00) and temperature (rs = 0.46; p = 0.02). On the contrary, leaf fall exhibited a negative correlation with precipitation (rs = -0.48; p = 0.02) among the three vegetative phenophases. The occurrence of flowering and flower fall also displayed positive correlations to precipitation (rs = 0.44; p = 0.03 and rs = 0.47; p = 0.02, respectively) and photosynthetically active radiation (rs = 0.51; p = 0.01 and rs = 0.56; p = 0.01, respectively). Apart from the aforementioned climatic parameters, there was also a significant positive correlation between flower fall and temperature (rs = 0.45; p = 0.03). However, among the three selected phenophases of fruiting, only fruit initiation showed positive correlations with precipitation (rs = 0.46; p = 0.02) and temperature (rs = 0.55; p = 0.01). Spearman's rank correlation analysis for each species revealed the absence of correlation of vegetative phases of *Dillenia indica, Magnolia hodgsonii* and *Toona ciliata* with climatic variables thereby signifying the evergreen characteristics. On the other hand, the vegetative phenophases of deciduous trees like *Bombax ceiba, Lagerstroemia speciosa, Sterculia villosa*, *Bauhinia purpurea*, *Gmelina arborea*, *Tectona grandis* and *Tetrameles nudiflora* were correlated with climatic variables, thereby highlighting deciduousness both as a response to and an adaptation to the climate. Table 4.4 provides details of correlation analysis between climatic variables and phenophases.

Table 4.4: Spearman's rank correlation analysis between climatic parameters and phenophases

Species	Phenophases	Precipitation (mm)		Temperature (°C)		Relative humidity (%)		Photosynthetically Active Radiation (W m^{-2})	
		r_s	p	r_s	p	r_s	p	r_s	p
Bauhinia purpurea	Leaf initiation	0.61*	0.02	0.79**	0.00	0.49**	0.01	0.63**	0.00
	Leafing	0.24	0.25	0.39	0.06	0.53*	0.01	0.13	0.55
	Leaf fall	-0.27	0.21	-0.03	0.88	0.35	0.10	-0.18	0.40
	Flower initiation	-0.32	0.12	-0.15	0.50	0.05	0.82	-0.05	0.82
	Flowering	-0.35	0.10	-0.15	-0.34	0.03	0.88	-0.04	0.84
	Flower fall	-0.54**	0.01	0.49	0.11	-0.19	0.37	-0.17	0.42
	Fruit initiation	-0.50**	0.01	-0.37	0.07	-0.14	0.53	-0.30	0.15
	Fruiting	-0.47*	0.02	-0.67**	0.00	-0.43*	0.04	-0.51**	0.01
	Fruit fall	-0.24	0.26	-0.22	0.30	-0.52**	0.01	-0.05	0.82
Bombax ceiba	Leaf initiation	0.10	0.65	0.35	0.10	0.60**	0.00	0.08	0.70
	Leafing	-0.20	0.36	0.01	0.95	0.50**	0.01	-0.24	0.27
	Leaf fall	-0.28	0.18	-0.13	0.54	0.11	0.61	-0.24	0.26
	Flower initiation	-0.23	0.27	-0.39*	0.06	-0.53**	0.01	-0.11	0.60
	Flowering	0.02	0.94	-0.11	0.60	-0.50**	0.01	-0.11	0.60
	Flower fall	0.02	0.94	-0.11	0.60	-0.50**	0.01	-0.11	0.60
	Fruit initiation	—	—	—	—	—	—	—	—
	Fruiting	0.17	0.42	-0.02	0.92	-0.22	0.31	0.04	0.84
	Fruit fall	0.29	0.17	0.13	0.55	-0.10	0.65	0.23	0.28
Dillenia indica	Leaf initiation	-0.11	0.62	-0.11	0.62	0.26	0.23	-0.35	0.10
	Leafing	—	—	—	—	—	—	—	—
	Leaf fall	—	—	—	—	—	—	—	—
	Flower initiation	0.36	0.09	0.61**	0.00	0.52**	0.01	0.45*	0.03
	Flowering	0.22	0.31	0.39	0.06	0.39	0.06	0.26	0.22
	Flower fall	0.22	0.31	0.39	0.06	0.39	0.06	0.26	0.22
	Fruit initiation	0.04	0.84	0.26	0.22	0.26	0.22	0.33	0.12

	Fruiting	0.05	0.82	0.21	0.33	0.31	0.07	0.24	0.25
	Fruit fall	-0.32	0.12	-0.15	0.50	0.05	0.82	-0.05	0.82
Gmelina arborea	Leaf initiation	-0.34	0.10	0.06	0.78	0.45*	0.03	0.04	0.87
	Leafing	-0.52**	0.01	-0.20	0.34	0.25	0.23	-0.11	0.62
	Leaf fall	—	—	—	—	—	—	—	—
	Flower initiation	0.18	0.40	-0.03	0.89	-0.51**	0.01	0.21	0.32
	Flowering	0.34	0.11	0.08	0.71	-0.24	0.25	0.21	0.33
	Flower fall	0.28	0.18	0.13	0.54	-0.11	0.61	0.24	0.26
	Fruit initiation	0.28	0.18	0.13	0.54	-0.11	0.61	0.24*	0.04
	Fruiting	0.48*	0.02	0.32	0.12	0.07	0.76	0.26	0.85
	Fruit fall	0.48*	0.02	0.30	0.15	0.24	0.26	-0.17	0.42
Lagerstroemia speciosa	Leaf initiation	0.78**	0.00	0.82**	0.00	0.38	0.07	0.66**	0.00
	Leafing	0.59**	0.00	0.76**	0.00	0.42*	0.04	0.67**	0.00
	Leaf fall	-0.07	0.76	0.05	0.81	0.59**	0.00	-0.26	0.22
	Flower initiation	0.34	0.11	0.08	0.71	-0.24	0.25	0.21	0.33
	Flowering	0.37	0.07	0.09	0.68	-0.09	0.69	0.12	0.59
	Flower fall	0.46*	0.02	0.15	0.47	0.33	0.11	-0.23	0.29
	Fruit initiation	0.55**	0.01	0.55**	0.01	0.40*	0.05	0.13	0.55
	Fruiting	0.18	0.40	0.43*	0.04	0.57**	0.00	0.38	0.07
	Fruit fall	-0.60**	0.00	-0.42*	0.04	-0.15	0.50	-0.32	0.12
Magnolia hodgsonii	Leaf initiation	—	—	—	—	—	—	—	—
	Leafing	—	—	—	—	—	—	—	—
	Leaf fall	—	—	—	—	—	—	—	—
	Flower initiation	0.56**	0.00	0.33	0.12	0.09	0.67	0.05	0.81
	Flowering	0.56**	0.00	0.56**	0.01	0.25	0.25	0.29	0.17
	Flower fall	0.40*	0.05	0.54**	0.01	0.26	0.23	0.33	0.12
	Fruit initiation	0.36	0.09	0.61**	0.00	0.52**	0.01	0.45*	0.03
	Fruiting	0.05	0.82	0.50**	0.01	0.57**	0.00	0.49*	0.02
	Fruit fall	-0.59**	0.00	-0.42*	0.04	-0.13	0.53	-0.34	0.11
Sterculia villosa	Leaf initiation	0.48*	0.02	0.75**	0.00	0.65**	0.00	0.53**	0.01
	Leafing	0.10	0.65	0.35	0.10	0.60**	0.00	0.08	0.70
	Leaf fall	-0.57**	0.00	-0.32	0.12	-0.10	0.65	-0.05	0.82

	Flower initiation	-0.24	0.26	-0.39	0.06	-0.53**	0.01	-0.13	0.54
	Flowering	0.02	0.94	-0.11	0.60	-0.50**	0.01	0.10	0.65
	Flower fall	0.02	0.94	-0.11	0.60	-0.50**	0.01	0.10	0.65
	Fruit initiation	0.17	0.42	-0.02	0.92	-0.22	0.31	0.04	0.84
	Fruiting	0.55**	0.01	0.31	0.14	0.08	0.70	0.07	0.76
	Fruit fall	0.48*	0.02	0.31	0.14	0.23	0.28	-0.16	0.44
Tectona grandis	Leaf initiation	0.58**	0.00	0.75**	0.00	0.64**	0.00	0.47*	0.02
	Leafing	0.22	0.30	0.37	0.08	0.63**	0.00	0.03	0.88
	Leaf fall	-0.23	0.29	0.05	0.83	-0.02	0.94	0.17	0.44
	Flower initiation	-0.03	0.90	0.25	0.25	0.30	0.15	0.32	0.13
	Flowering	0.05	0.81	0.20	0.35	0.38	0.07	0.22	0.29
	Flower fall	0.05	0.81	0.20	0.35	0.38	0.07	0.22	0.29
	Fruit initiation	-0.30	0.15	-0.19	0.37	-0.03	0.90	-0.10	0.64
	Fruiting	-0.84**	0.00	-0.86**	0.00	-0.71**	0.00	-0.54**	0.01
	Fruit fall	0.08	0.70	0.09	0.69	-0.62**	0.00	0.37	0.07
Tetrameles nudiflora	Leaf initiation	0.15	0.48	0.13	0.54	0.46*	0.03	-0.09	0.69
	Leafing	0.15	0.48	0.13	0.54	0.46*	0.03	-0.09	0.69
	Leaf fall	-0.60**	0.00	-0.26	0.21	0.06	0.80	-0.07	0.75
	Flower initiation	-0.15	0.47	-0.13	0.54	-0.46*	0.03	0.08	0.71
	Flowering	0.17	0.42	-0.02	0.92	-0.22	0.31	0.04	0.84
	Flower fall	0.17	0.42	-0.02	0.92	-0.22	0.31	0.04	0.84
	Fruit initiation	0.17	0.42	-0.02	0.92	-0.22	0.31	0.04	0.84
	Fruiting	0.57**	0.00	0.32	0.12	0.10	0.65	0.05	0.82
	Fruit fall	0.48*	0.02	0.31	0.15	0.24	0.26	-0.17	0.42
Toona ciliata	Leaf initiation	0.24	0.25	0.39	0.06	0.53**	0.01	0.13	0.55
	Leafing	—	—	—	—	—	—	—	—
	Leaf fall	—	—	—	—	—	—	—	—
	Flower initiation	-0.15	0.48	-0.13	0.54	-0.46*	0.03	0.09	0.69
	Flowering	0.17	0.42	-0.02	0.92	-0.22	0.31	0.04	0.84
	Flower fall	0.17	0.42	-0.02	0.92	-0.22	0.31	0.04	0.84
	Fruit initiation	0.57**	0.00	0.32	0.12	0.10	0.65	0.05	0.82

	Fruiting	0.55^{**}	0.01	0.55^{**}	0.01	0.40^{*}	0.05	0.13	0.55
	Fruit fall	0.26	0.22	0.44^{*}	0.03	0.31	0.15	0.35	0.10
Multi-species (overall)	Leaf initiation	0.43^{*}	0.03	0.76^{**}	0.00	0.80^{**}	0.00	0.52^{**}	0.01
	Leafing	0.05	0.83	0.46^{*}	0.02	0.68^{**}	0.00	0.30	0.16
	Leaf fall	-0.48^{*}	0.02	-0.16	0.44	0.30	0.15	-0.13	0.54
	Flower initiation	0.26	0.22	0.09	0.67	-0.35	0.10	0.32	0.13
	Flowering	0.44^{*}	0.03	0.40^{*}	0.05	-0.07	0.75	0.51^{**}	0.01
	Flower fall	0.47^{*}	0.02	0.45^{*}	0.03	-0.11	0.61	0.56^{**}	0.01
	Fruit initiation	0.46^{*}	0.024	0.55^{**}	0.01	0.37	0.07	0.31	0.14
	Fruiting	0.20	0.35	0.17	0.43	0.13	0.56	0.11	0.60
	Fruit fall	-0.09	0.68	-0.02	0.94	-0.31	0.15	-0.04	0.86

4.3.4 Seasonality of phenophases

The phenological data was put through the Rayleigh test, which showed that of the 9 phenophases chosen for this study, leaf initiation ($Z = 3.28$, $p = 0.04$) and flowering ($Z = 3.75$, $p = 0.02$) had non-uniform peak distributions (Table 4.5). The circular plots of the phenological data demonstrated that all 10 species exhibited vegetative phenophases simultaneously from July to October (Fig. 4.3). As illustrated in Fig. 4.3, all 10 species exhibited a consistent leaf fall phenophase from July to February. Regarding the reproductive phenophases of flowers and fruits, however, the fact that none of the chosen tree species occurred at the same time indicates that there are distinct variances among the species. This is because the phenophases of flowers and fruits are not the same for all the studied species. The Rayleigh test for individual species demonstrated that non-uniform distributions were observed for one or more vegetative phenophases except in *Dillenia indica, Magnolia hodgsonii* and *Toona ciliata* (Table 4.5). On the other hand, all the tree species displayed non-uniform reproductive phenophases. The Rayleigh test for fruit initiation of *Bombax ceiba* was indeterministic implying a brief period of transition from flower fall to fruiting.

Table 4.5: Circular statistical analysis of the phenological data of selected tree species

Species	Phenophases	Rayleigh Test (Z)	Rayleigh Test (p)	Mean angle	Month
Bauhinia purpurea	Leaf initiation	4.68	0.01**	198.50	July
	Leafing	1.91	0.15	240.00	August
	Leaf fall	2.25	0.11	296.10	October
	Flower initiation	9.55	0.00**	300.00	October
	Flowering	8.60	0.00**	301.71	November
	Flower fall	7.67	0.00**	326.17	November
	Fruit initiation	7.67	0.00**	333.83	December
	Fruiting	12.36	0.00**	30.00	January
	Fruit fall	5.91	0.00**	70.13	March
Bombax ceiba	Leaf initiation	4.24	0.01**	255.00	September
	Leafing	4.24	0.01**	285.00	October
	Leaf fall	0.47	0.63	315.00	November
	Flower initiation	8.60	0.00**	61.71	March
	Flowering	9.55	0.00**	90.00	March
	Flower fall	9.55	0.00**	90.00	March
	Fruit initiation	—	—	—	—
	Fruiting	5.00	0.00**	105.00	April
	Fruit fall	4.00	0.00**	135.00	May
Dillenia indica	Leaf initiation	0.07	0.93	315.00	November
	Leafing	—	—	274.09	October
	Leaf fall	—	—	274.09	October
	Flower initiation	9.55	0.00**	210.00	July
	Flowering	5.00	0.00**	225.00	August
	Flower fall	5.00	0.00**	225.00	August
	Fruit initiation	5.00	0.00**	255.00	September
	Fruiting	9.55	0.00**	270.00	September
	Fruit fall	9.55	0.00**	300.00	October
Gmelina arborea	Leaf initiation	10.18	0.00**	285.00	October
	Leafing	5.76	0.00**	305.28	November
	Leaf fall	—	—	274.09	October
	Flower initiation	8.93	0.00**	101.93	April
	Flowering	9.55	0.00**	120.00	April
	Flower fall	5.00	0.00**	135.00	May

	Fruit initiation	5.00	0.00^{**}	135.00	May
	Fruiting	6.77	0.00^{**}	156.55	June
	Fruit fall	5.00	0.00^{**}	165.00	June
Lagerstroemia speciosa	Leaf initiation	7.16	0.00^{**}	180.00	June
	Leafing	5.19	0.00^{**}	201.74	July
	Leaf fall	2.66	0.07	277.28	October
	Flower initiation	9.55	0.00^{**}	120.00	April
	Flowering	6.77	0.00^{**}	126.55	May
	Flower fall	4.79	0.00^{**}	153.07	June
	Fruit initiation	9.55	0.00^{**}	180.00	June
	Fruiting	12.73	0.00^{**}	255.00	September
	Fruit fall	9.55	0.00^{**}	330.00	November
Magnolia hodgsonii	Leaf initiation	—	—	274.09	October
	Leafing	—	—	274.09	October
	Leaf fall	—	—	274.09	October
	Flower initiation	8.60	0.00^{**}	151.71	June
	Flowering	11.28	0.00^{**}	169.79	June
	Flower fall	6.77	0.00^{**}	186.55	July
	Fruit initiation	9.55	0.00^{**}	210.00	July
	Fruiting	14.25	0.00^{**}	255.00	September
	Fruit fall	8.60	0.00^{**}	331.71	December
Sterculia villosa	Leaf initiation	10.18	0.00^{**}	225.00	August
	Leafing	4.24	0.01^{**}	255.00	September
	Leaf fall	1.91	0.15	330.00	November
	Flower initiation	8.60	0.00^{**}	58.30	February
	Flowering	9.55	0.00^{**}	90.00	March
	Flower fall	9.55	0.00^{**}	90.00	March
	Fruit initiation	5.00	0.00^{**}	105.00	April
	Fruiting	7.67	0.00^{**}	146.17	May
	Fruit fall	4.00	0.01^{**}	165.00	June
Tectona grandis	Leaf initiation	7.22	0.00^{**}	214.24	August
	Leafing	1.81	0.16	242.73	September
	Leaf fall	0.07	0.93	285.00	October
	Flower initiation	7.67	0.00^{**}	266.17	September
	Flowering	8.60	0.00^{**}	271.71	October
	Flower fall	8.60	0.00^{**}	271.71	October

	Fruit initiation	7.67	0.00^{**}	303.83	November
	Fruiting	13.74	0.00^{**}	18.07	January
	Fruit fall	9.44	0.00^{**}	108.83	April
Tetrameles nudiflora	Leaf initiation	0.47	0.63	255.00	September
	Leafing	0.47	0.63	255.00	September
	Leaf fall	4.24	0.01^{**}	315.00	November
	Flower initiation	4.00	0.01^{**}	75.00	March
	Flowering	5.00	0.00^{**}	105.00	April
	Flower fall	5.00	0.00^{**}	105.00	April
	Fruit initiation	5.00	0.00^{**}	105.00	April
	Fruiting	9.55	0.00^{**}	150.00	May
	Fruit fall	5.00	0.00^{**}	165.00	June
Toona ciliata	Leaf initiation	1.91	0.15	240.00	August
	Leafing	—	—	274.09	October
	Leaf fall	—	—	274.09	October
	Flower initiation	5.00	0.00^{**}	75.00	March
	Flowering	5.00	0.00^{**}	105.00	April
	Flower fall	5.00	0.00^{**}	105.00	April
	Fruit initiation	9.55	0.00^{**}	150.00	May
	Fruiting	9.55	0.00^{**}	180.00	June
	Fruit fall	5.00	0.00^{**}	195.00	July
Overall	Leaf initiation	3.28	0.04^{*}	229.52	August
	Leafing	1.57	0.21	256.67	September
	Leaf fall	0.92	0.40	304.11	November
	Flower initiation	2.65	0.07	105.00	April
	Flowering	3.75	0.02^{*}	131.57	May
	Flower fall	2.85	0.06	135.00	May
	Fruit initiation	1.47	0.23	206.57	July
	Fruiting	0.04	0.96	195.00	July
	Fruit fall	0.35	0.71	113.79	April

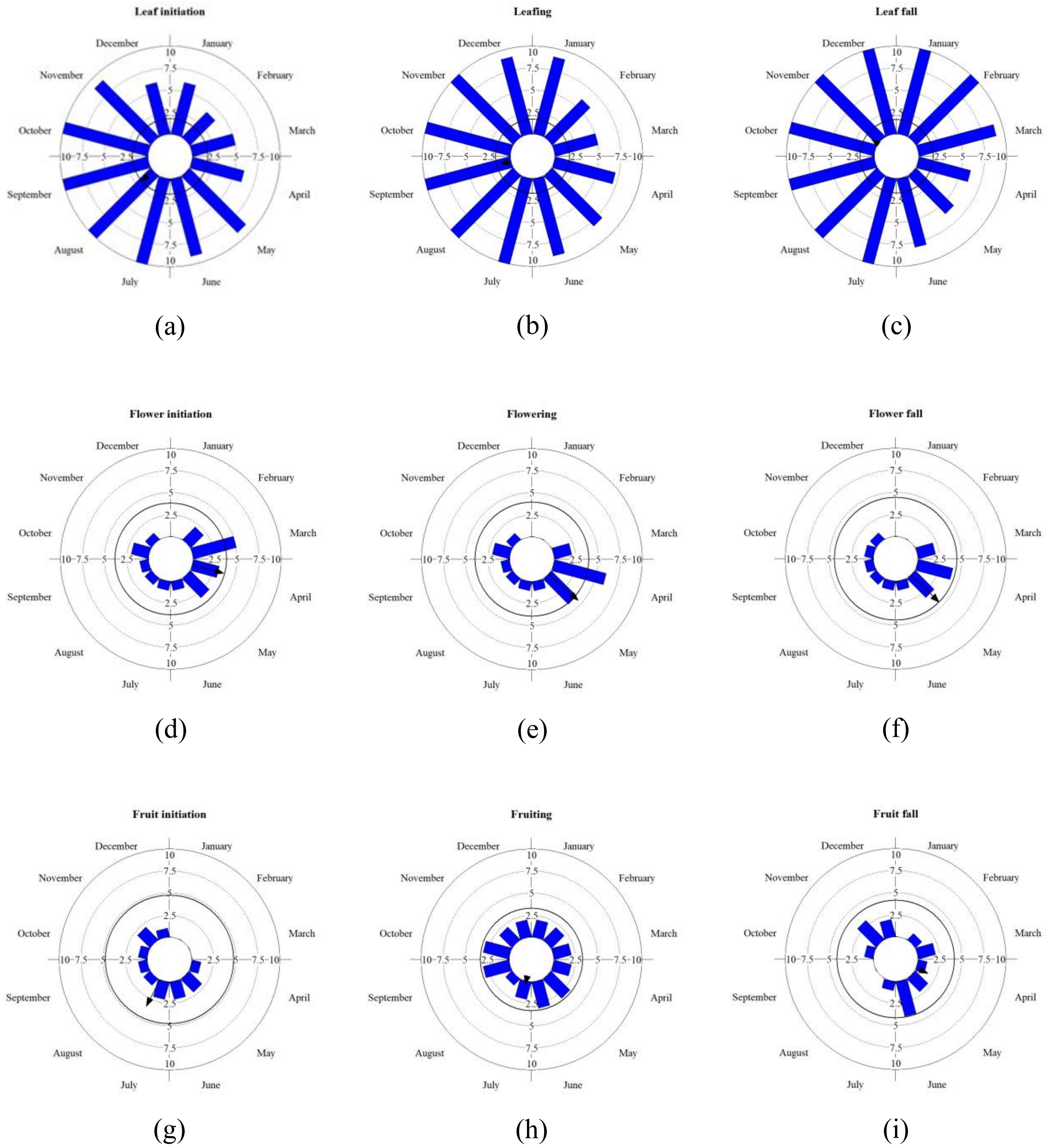

Fig. 4.3: Circular plots representing nine phenological data points for the studied tree

4.4 Discussion

4.4.1 Vegetative phenophase and climatic variables

The trees with evergreen traits are attributed with either one or two vegetative phenophases throughout the year. However, different plant species have different phenological responses to climate factors. Studying vegetation phenology as a whole is a great way to understand how plant functions are connected to climate factors like temperature and rainfall, both on a global and regional level [30,31]. The association of phenophases' occurrences with seasonal variations in climatic parameters enables the plants to maximize the resources utilization of things like water and light availability while mitigating the negative impact of unfavourable seasonal conditions like drought. This study demonstrates a positive correlation between leaf initiation, precipitation, relative humidity, temperature, and photosynthetically active radiation, and these factors serve as phenological cues for the onset of leaf initiation.

It has been observed in present study that March onwards, resurgence in leaf initiation and leafing was observed as all the tree species displayed different vegetative phenophases. This resurgence coincided with the increase in monthly precipitation as well as monthly mean temperature, relative humidity and photosynthetically active radiation. Meanwhile, the vegetative phenophases i.e. leaf initiation, leafing, and leaf fall, declined during the period from November to May, characterized with low temperature, precipitation, relative humidity and photosynthetically active radiation. Several researcher Devi and Garkoti [19], Bhat et al. [32], Kikim and Yadava [33], and Chakrabarty et al. [34] have recorded similar observations, indicating tree species showing peaked leaf initiation during March to June are characterized by an increase in both precipitation and temperature, along with an increase in relative humidity and photosynthetically active radiation. These studies in different parts of India indicate that these climatic parameters promote the process of photosynthesis and vegetative growth. According to Rawal et al. [35], the increases in temperature signify the termination of the winter dormancy of vegetative buds. Similarly, the positive association between leafing and relative humidity and temperature allows the species to effectively utilize favourable conditions during the monsoon period for productivity [29]. Shukla and Ramakrishnan [24] found that bud-burst begins during the pre-monsoon, but leaf development reaches its peak at the beginning of the rainy (monsoon) season. Similarly, Chanda et al. [36] noted that noted that rainfall and temperature changes significantly influenced the phenophases associated with vegetative growth in the Eastern

Himalayan region, highlighting the role of climatic variables as cues for vegetative phenophases.

There were fewer species showing leaf initiation and leafing than leaf fall during the winter and at the beginning of the premonsoon. This suggests that leaf fall is associated with the cooler climates, as indicated by studies conducted by Huxley and Van Eck [37], Huxley [38], Kikim and Yadav [33], and Das and Das [25]. The presence of a negative correlation of leaf fall with precipitation indicates that the trees have developed leaf fall as an adaptation to minimize the impact of drought stress and maintain shoot turgidity [25]. Borchert [39] asserts that the process of senescence and the shedding of leaves might potentially reduce the amount of water lost by transpiration. The reduction in transpiration, which lowers water loss, promotes a rise in the water potential of trees, subsequently resulting in bud breaking. Therefore, the seasonal variations of climatic parameters, specifically precipitation (rainfall), can significantly influence the periodic patterns of vegetative growth in tropical forests [40].

4.4.2 Reproductive phenophases and climatic variables

A peak flowering was observed prior to the onset of the monsoon. However, a single distinct seasonal peak was not observed for fruit initiation, fruiting, and fruit fall, but rather two small peaks were observed (Table 4.3). According to Fenner [41], reproductive events usually occur either when photosynthetic activity is low or after a period of rapid reserve accumulation. The time lag between the occurrence of vegetative and reproductive phenophases signifies the separation and allocation of resources within trees [42,43,44]. The absence of any correlation between flower initiation and climatic parameters suggests that vegetative phenophases play a pivotal role in determining the occurrence of flower phenophases [45]. The present investigation revealed a positive correlation of flowering with both precipitation and photosynthetically active radiation. Flowering reached its highest peak during April and May, showing a distinct seasonal pattern of the phenophase. This observation resonates with the research conducted by Wright and Van Schaik [12] and Wright [46], which established the associations of seasonal variations in solar irradiance and precipitation with the flowering phenophase of tropical forests [47]. Similarly, the fact that flower fall is positively correlated to precipitation, temperature and photosynthetically active radiation confirms that these are important for indicating reproductive phenophases. Van Schaik's [48] isolation-limitation hypothesis is supported by the fact that flower-related phenophases are linked to both precipitation and photosynthetically active radiation. This hypothesis suggests that in tropical forests, the timing of leafing and flowering aligns with the period of highest solar radiation unless restricted by water availability. This finding is consistent with the research conducted by Suresh and Sukumar [49]. Also, studies have shown that drought and temperature regulate the expression of genes associated with the timing of flowering thereby highlighting the potential role of water stress and temperature changes as phenological cues [50,51,52].

In this study, fruit initiation phenophase showed positive correlations with both precipitation and temperature. However, the absence of distinct seasonal peaks for occurrence of fruiting and fruit fall, along with the absence of correlations with climatic parameters, signifies that the studied tree species have diverse fruiting durations. Tropical and sub-tropical regions often spread the onset and duration of fruiting over multiple seasons, resulting to unclear peaks [52]. Furthermore, according to Singh and Kushwaha [43], species that flower under different seasonal variations of climatic parameters exhibit different fruiting durations. These differences in the occurrences of fruiting and fruit fall reflect the genetic influence and adaptations of the species to the biotic and abiotic environmental conditions that ensure successful germinations and establishments during favourable seasons [52].

4.5 Conclusion

The study of the phenophases of the trees that characterize the tropical semi evergreen forest demonstrated that the presence of positive or negative associations of the phenophases with climatic variables indicate that the onsets of many phenophases were cued by the fluctuations in the climatic variables. Although the phenophases of the individual species demonstrated non-uniform distribution, exceptions were observed regarding the vegetative phenophases in the evergreen tree species. The overall display of non-uniform distribution only in leaf initiation and flowering implies that the occurrences and durations of phenophases such as flower initiation, flower fall fruit initiation, fruiting, fruit fall, etc. varied with species. Thus, phenophases are species-specific responses of the trees and the floristic composition of the forest determines the overall exhibited distributions of phenophases in relation to the climatic conditions of the region.

4.6 References

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