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Research article

Phenological variations in relation to climatic variables of moist temperate forest tree species of western Himalaya, India

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ABSTRACT

Phenology, an important ecological attribute, deals with the development of vegetative and reproductive parts of trees called “phenophases”, which are important determinants of primary productivity and sensitive to climate change. The present study recorded various phenophases of major tree species (i.e., *Quercus leucotrichophora*, *Rhododendron arboreum,* and *Myrica esculenta*) as per the two-digit numerical system of Biologische Bundesanstalt, Bundessortenamt, Chemische Industrie (BBCH) scale. A total of 72 individual trees, twenty-four from each species, distributed between 1400 and 1980 m. a.s.l elevations were tagged and measured fortnightly for two consecutive years (2019–2021) in the moist temperate forest of Western Himalaya and compared with earlier existing records. Various phenophases were correlated with climatic factors along with duration and thermal time for each phenological growth stage. We found 24 growth stages for *Q. leucotrichophora* and *M. esculenta* and 28 for *R. arboreum* distributed across seven principal growth stages (e.g. bud development, 0; leaf development, 1; shoot development, 3; inflorescence development, 5; flower development, 6; fruit development, 7; and fruit maturation, 8) of trees as per BBCH scale. Maximum growing degree was 748.87 and 627.95 days recorded for *R. arboreum* and *M. esculenta* during leaf development, and 796.17 days for *Q. leucotrichophora* during fruit development. Flower emergence was observed pre, during, and post-emergence of new leaves for *R. arboreum*, *M. esculenta,* and *Q. leucotrichophora*, respectively, which varied at spatial scale with previous findings. Longevity of fruit development to ripening took 17, 4, and 2 months, respectively in *Q. leucotrichophora*, *R. arboreum* and *M. esculenta*. Duration of leaf initiation and flowering was positively correlated with climatic variables, whereas, the reverse was observed for fruiting in the studied tree species. The study concludes that the variations in phenophases of the three species were strongly influenced by climatic variations, especially minimum temperature. The result of the present study would be important in enabling us to formulate efficient forest management strategies by understanding the short-term adaptation of the climate-sensitive important tree species in the western Himalaya.

1. Introduction

Phenological events are the outcome of the adapatation of plant species to abiotic conditions (temperature, sunshine, length of

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photoperiod, humidity, winter chilling etc.) in a particular habitat [1,2], and therefore, these phenological events (leafing, flowering, fruiting, etc.) are sensitive to climate change [3,4]. Phenological events govern both short-term and long-term adaptive evolution and strategy in plants by facilitating a buffer against elevation and climate change [5]. Therefore, tree phenological events act as an early indicator of plant response to climate change in the forest ecosystem [6]. The tree species in temperate forests are well adapted to the low temperature, and thus during the future climate change scenario particularly, the increase in temperature may profoundly affect the vegetative and reproductive phenology of the tree species in Asia [7], Europe [8] and North America [9]. Such changes in phenological events at plant and community level are reported to alter community interactions, and thereby carbon uptake and reproductive biology of the trees [10]. Such changes will significantly affect ecosystem processes (i.e. cycles of water, carbon, and nutrients) and thereby their services to society at various spatial scales [11,12]. Recently, phenological changes have been reported to adversely affect the plant growth, carbon balance and productivity of temperate and tropical forests [13]. Therefore, it is important to understand the shift in phenological events in trees in different regions and to formulate proper scientific strategies for the management and conservation of forests in different regions of the world [14].

In temperate ecosystems, plant phenological events are found to be sensitive to environmental factors such as photoperiod, temperature, and winter chilling [15]. For example, temperature and day length together affect tree leafing pattern [16], spring temperature (forcing temperature) and late frost affect rate of bud burst [15] and spring temperature variability affects the phenological patterns of the plant [17]. Thus, changes in environmental factors are critical in determining the response of tree phenological events such as the onset, peak, and end of the phenological events as well as their durations [18]. The phenological study provides information on ecosystem response to seasonal climatic conditions, and changes in climate such as spring advancement and autumn postponement has been reported to shift the timing of major phenological events [19]. Besides, elevation is also a significant factor affecting plant phenology due to the interaction of biotic (i.e. flora and fauna) and abiotic (i.e. temperature, precipitation and moisture) components [20]. Further, phenology, development and adaptive capacity of plants have been reported to be altered at elevation gradient which results to influence species longevity. For instance, changes in physiographic features of a species can affect pollination patterns by affecting reproductive mechanism, which leads to shifts in phenological patterns such as early or late flowering, seed set, and bud formation [21].

Biologische Bundesanstalt, Bundessortenamt, Chemische Industrie (BBCH) is an approach to investigate the phenological observations on a scale of 0–9 [22], which has been widely used to describe the phenological stages for different tropical and temperate plants over the world [23]. The scale describes the plant growth stages in a uniform decimal code on two scales [24]. The primary scale describes the Principal Growth Stages (PGS) of plant development such as bud development, shoot development, flowering, and fruit development, whereas the secondary scale is a subset of the principal stages [25].

The present study evaluates the phenological growth stages in the ecologically sensitive moist temperate forest of Western Himalaya where the warming effects are 2–3 times higher than the global mean temperature in recent decades [26]. The tree species like i.e. *Quercus leucotrichophora* A. Camus, *Rhododendron arboreum* Smith and *Myrica esculenta* Buch. -Ham. ex. D. Don are ecologically and economically important for the livelihood of inhabitants of Western Himalaya. Therefore, phenological events studied for these selected tree species are of high importance for ecosystem services such as soil and water conservation, fuel, fodder, and nutritious diet. This study hypothesizes that the phenological events of the selected tree species shift with changing climatic parameters (i.e., temperature and precipitation patterns) will affect survival, growth, carbon balance and composition of the forest ecosystem. The studied objectives led to create databases for phenological growth stages of three tree species through the BBCH scale for wider comparison along with evaluation of change in phenophases in future studies. The findings will facilitate information for the effective forest management under the present climate.

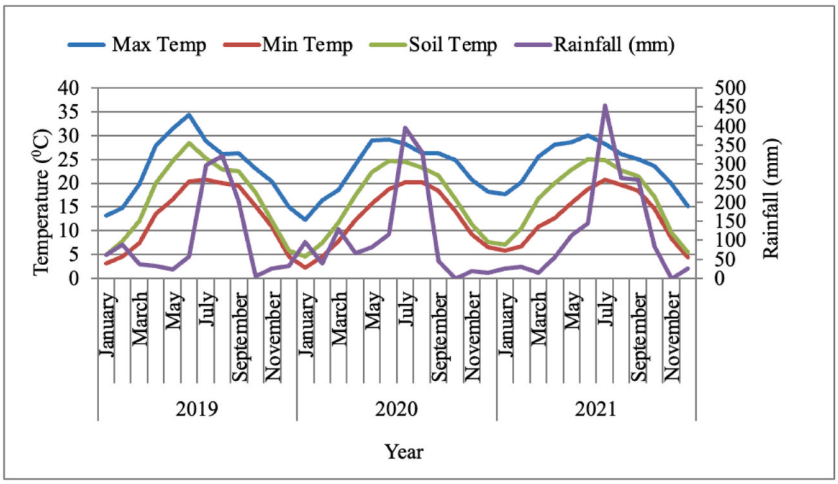


Fig. 1. Minimum and maximum air temperature (°C), soil temperature (°C) and rainfall (mm) for the period from 2019 to 2021 (Source: http://power.larc.nasa.gov).

2. Materials and methods

2.1. Study site

The phenological study was conducted in the moist temperate forest situated at Mussoorie Forest Division, Uttarakhand, with an area of lying 210 ha between 30,^{0}20′34.06″and 30°2′50.53″ N latitude and 78,^{0}09′23.21″ - 78°12′29.16″ E longitude. The focus of the study was Banj – oak forest, which is one of the important land use types in the Western Indian Himalayan region of Uttarakhand and Himachal Pradesh constituting 13.75 and 3.97% of the total forest area, respectively. Climate of the study area is characterized by three distinct seasons viz., monsoon (July–October), winter (November–December) and summer (March–June). The total annual rainfall varied from 1333.59 mm to 1484.83 mm during 2019–20 and 2020–21. The mean annual minimum and maximum air temperate ranged between 12.42 °C and 22.77 °C during 2019–20 and 12.84 °C and 24.10 °C during 2020–21, respectively (Fig. 1) (https://power.larc.nasa.gov/). The soil is dark brown to dark yellowish-brown in color and had a higher potential water-holding capacity [27]. A total of 61 plant species were recorded through a vegetation survey in the banj oak-dominated forest, of which 4 were present in tree form, 14 as shrubs and 43 as herbs. Dominant species is *Q. leucotrichophora*, whereas, codominant species are *R. arboreum* and *M. esculenta*. Underground vegetation are *Drepanostachyu falcatum, Ageratina adenophora, Debregeasia longifolia, Boehmeri rugulosa* and *Berberis* spp etc.

2.2. The species

In the present study, three major tree species like *Q. leucotrichophora*, *R. arboreum*, and *M. esculenta* were evaluated for their distribution and characteristics as reported in Table 1.

Q. leucotrichophora (family: Fagaceae) is an evergreen tree locally known as banj oak with full and rounded canopy. The bark is initially smooth tan-brown and becomes lightly furrowed and corky with age. Young leaves are pink-purple, and as they mature, the upper surface turns deep green, while the lower side is silvery grey due to the presence of white hairs. The fruits are marble-sized orange-tan acorns. It grows to a height of 15–25 m in all aspects with high preference to the northern aspects [28]. *R. arboreum* (family: Ericaceae) is a small evergreen tree known locally as Burans. The leaves are stiffly leathery, oblong-lanceolate to oblong-oblanceolate, and usually silvery white. Flower is red. Burans magnificent flowers are most valuable non-timber forest products and a source of income for the locals of the Himalayan region [29]. *M. esculenta* (family: Myricaceae) is a dioecious tree species locally or commonly known as box berry or kaphal having high medicinal value (Table 1). A small to medium-sized evergreen tree attains a height of 6–8 m. The outer bark is greyish-dark, rough, and vertically wrinkled, whereas the inner bark is dark brown with a smooth surface. The leaves are lanceolate, pale green on the lower surface and dark green on the upper surface. The fruit is red to dark brown in color and ellipsoidal or oval in shape. The ripe fruit is extremely sour and is consumed raw or dried and is also used to prepare pickles and fruit juice [30].

3. Methods

3.1. The BBCH scale

Developmental stages and morphological characteristics were recorded as per the extended BBCH scale. BBCH scale was selected with its comprehensiveness along the development stages of plant development and is based on a two-digit code that considers 10 Principal Growth Stages (PGS) (macro stages) numbered from 0 to 9. The first digit describes the principal growth stage (0–9) and describes 10 recognizable and distinguishable long-lasting developmental phases. The second digit describes the secondary stage (0–9) or points of time or steps of plant development [31]. The recommended extended BBCH phenological scale for *Q. leucotrichophora*, *R. arboreum* and *M. esculenta* consists of seven major growth stages: 0 (vegetative bud development), 1 (leaf development), 3 (shoot

Table 1
Distribution and ecological characteristics of selected tree species of temperate forest.

Scientific/Local name	Present study		Habitat	Altitude (m. a.s.l)	Distribution		Source
	DBH (m)	Height (m)			India	Other country	
Q. leucotrichophora (Banj oak)	0.35 ± 0.02 (0.24–0.42)	16.80 ± 0.95 (11.50–22.45)	Dense, pure or mixed stands	1200–2300	HP, UK	Bhutan, Nepal	Singh and Singh 1986
R.arboreum (Burans)	0.23 ± 0.02 (0.14–0.27)	11.48 ± 1.08 (8.05–12.30)	Open or mixed forest and pure stands	1500–3500	AP, HP, JK, Ma, Meg, Mi, Nag, Si, UK and WB	Bhutan, China, Myanmar, Nepal, Sri Lanka, Thailand and Vietnam	Paul et al., 2018
M. esculenta (Kafal)	0.26 ± 0.01 (0.21–0.28)	10.64 ± 0.82 (7.20–9.55)	Pine, pure and mixed oak forest	900–2100	As, HP, Ma, Meg, Mi, Nag, Si, UK	Bhutan, Malaya, Nepal, Singapore, China and Japan	Sood and Shri 2018

*As = Assam; AP = Arunachal Pradesh; HP = Himachal Pradesh; JK = Jammu and Kashmir; Ma = Manipur; Meg = Meghalaya; Mi = Mizoram; Nag = Nagaland; Si = Sikkim; UK = Uttarakhand; WB = West Bengal.
*Value within the parenthesis is minimum and maximum.

development), 5 (inflorescence emergence), 6 (flowering), 7 (fruit development), and 8 (fruit maturity). However, phenological growth stages 2 (side branch formation/tillering), 4 (growth of harvestable vegetative plant parts), and 9 (senescence, onset of dormancy) were not considered because tree species did not display the phases. Based on field observations, a number of PGS were observed during the study period for the species. The PGS for *Q. leucotrichophora* was divided into six stages; three for vegetative growth (i.e. bud, leaf and shoot development) and three for reproductive stages (i.e. inflorescence emergence, flowering, fruit development and fruit maturation). *R. arboreum* were divided into seven stages; three for vegetative growth (i.e., bud, leaf and shoot development) and four for reproductive stages (i.e., inflorescence emergence, flowering, fruit development and fruit maturation). *M. esculenta,* it was divided into six stages; two for vegetative growth (i.e., leaf and shoot development) and four for reproductive stages (i. e., inflorescence emergence, flowering, fruit development and fruit maturation). Flowering synchrony is the degree to which one plant's peak flowering phase overlapped with every other plant's peak in the population. The synchrony index of each species was calculated using the ratio of the mean length of the phenological phase for each individual to the overall length of the phenophase. A high synchrony index value indicates a likelihood of coincident phenological stages amongst individuals in a population for a given species of tree.

3.2. Phenological observations

A total of seventy-two individual trees of 3 functionally different key tree species (24 individual of a species x 3 species), namely *Q. leucotrichophora*, *R. arboreum* and *M. esculenta* were selected and marked with aluminum plates in October 2019. The selection of

Table 2
Description of phenological growth stages, duration and heat unit requirement (growing degree day) for different phenological growth stages of major tree species of moist temperate forest.

BBCH code description	*Q. leucotrichophora*		*R. arboreum*		*M. esculenta*	
	Day	GDD	Day	GDD	Day	GDD
Principal growth stage 0: Vegetative bud development	84	766.79	56	499.75		
01 Beginning of bud swelling	24	229.8	12	114.90	–	–
02 Beginning of bud elongation	33	303.435	9	82.76	–	–
05 End of bud elongation	27	233.55	10	86.50	–	–
07 Beginning of bud break	–	–	13	112.52	–	–
09 End of bud break	–	–	12	103.08	–	–
Principal growth stage 1: Leaf development	98	795.18	91	748.87	70	627.95
010 Leaf tip start to visible	10	85.9	–	–	–	–
011 First leaf emerging	14	134.82	–	–	–	–
013 More leaves unfolded: petioles visible	17	142.545	16	154.08	13	124.475
015 Leaves more than 50% of their full size	22	172.7	31	259.94	19	174.705
017 Leaves more than 80% of their full size	16	116.72	25	196.25	23	198.95
019 Leaves turn dark green with completely expanded lamina	19	142.5	19	138.61	15	129.825
Principal growth stage 3: Shoot development	84	638.81	54	413.33	56	462.12
032 Advance shoot extension and 10% of final length	13	103.09	–	–	15	144.45
033 Shoots about 30% of final length	21	164.325	15	118.95	9	75.465
035 Shoot more than 50% of its final length	15	113.625	10	78.25	11	86.35
035 Shoot more than 70% of its final length	17	123.76	17	128.78	8	58.36
039 Completely developed shoots	18	134.01	12	87.36	13	97.5
Principal growth stage 5: Inflorescence development	42	312.48	35	245.12	35	245.12
051 Emerging phase of panicle (*Q. leucotrichophora*)/corymb (*R. arboreum*)/florat (*M. esculenta*)	42	312.48	9	67.37	9	67.37
053 Corymb/florat about 30% of full size	–	–	8	59.52	8	59.52
055 Corymb/florat about 50% of full size	–	–	11	73.65	11	73.65
059 Full size of corymb/florat has been developed	–	–	7	44.59	7	44.59
Principal growth stage 6: Flowering	36	229.32	42	251.09	56	374.49
060 Development of flowering bud/flower opening	–	–	7	45.64	5	37.425
061 First flower open	–	–	5	31.13	11	81.84
062 Beginning of flowering: 10% of full flowers	36	229.32	8	44.20	8	53.56
065 Flower corymb more than 50%	–	–	10	54.45	9	57.33
067 Full flowering	–	–	5	29.73	10	61.35
068 End of flowering: all petals fallen or dry, fruit set	–	–	–	–	7	45.64
069 Pollen dehiscence completed/Barren panicle	–	–	7	45.96	6	37.35
Principal growth stage 7: Fruit development	133	796.17			21	125.18
073 Fruit/acorn (*Q. leucotrichophora*) at 10% of final size	35	228.2	–	–	8	43.56
075 Fruit/acorn at 50% of final size, end of physiological fruit drop	41	255.22	12	73.74	6	35.67
077 Fruit/acorn at 70% of final size, end of physiological fruit drop	30	165.75	–	–	–	–
079 Full Fruits/acorn size and advanced color change	27	147.01	9	59.81	7	45.955
Principal growth stage 8: Fruit maturation	70	456.27	16	99.57	35	111.03
081 Beginning of fruit/acorn maturation	15	98.475	10	62.85	21	129.045
085 Advance color development	24	160.8	6	36.72	14	93.03
087 70% advance maturation	18	110.61	–	–	–	–
089 Fruit/acorn over mature and falling	13	86.385	–	–	–	–

*GDD = Growing degree day, Day = Duration.

individuals of each studied species was based with approximately equivalent tree height and diameter (DBH) and distributed between 1400 and 1980 m. a.s.l elevations. The phenological observations of the experimental sites were made regularly at fortnightly intervals for two years (i.e., from autumn 2019 to autumn 2021). DBH (m) of *Q. leucotrichophora*, *R. arboreum* and *M. esculenta* ranged from 0.351 to 0.343, 0.237 to 0.309, and 0.218 to 0.268, respectively, whereas, the height (m) of these three species ranged from 16.80 to 17.43, 11.48 to 14.22 and 10.64 to 9.84, respectively (Table 1). The average horizontal distance between two selected individuals was maintained around 50 m to cover spatial heterogeneity. Individuals' trees were observed for both vegetative (foliar) and reproductive (flower and fruit) phenologies. Vegetative and reproduction phenologies were considered in a particular phenophase when more than 50% of the individuals of that species passed through that phase. Flowering phenophases included flower bud, flower ripening, and flowers maturation whereas fruit phenophases include fruit ripening/unripened fruit and matured fruit/ripened [31]. Phenophase of a

Fig. 2. aPhenological growth stages of evergreen tree species of moist temperate forest in the study site of Uttarakhand. a: *Q. leucotrichophora* with different phenophases and codes.

species was determined by considering the status of the majority of individuals [32]. The range of period for each phenological stage was used for detailing the various phenological stages from the observed data of all individuals of the species. The duration of a phenological event in a species was computed by counting the number of days required for the completion of an event from the first observation of the event during the date of the fortnightly visit.

3.3. Meteorological observation

The meteorological parameters (i.e., minimum and maximum air temperature, soil temperature and rainfall) were obtained from Worldwide Energy Resources (POWER) Project of NASA (https://power.larc.nasa.gov/) for the period ranging from 2019 to 2021. The climatic data as minimum and maximum air temperature and soil temperature were having consistent pattern across the three years whereas rainfall was having an increasing pattern from year 2019–2021 (Fig. 1).

3.4. Data analysis

The Growing Degree Days (GDD) index was used to accurately examine the plant's phenological stages (Zafarian et al., 2019). Based on the local meteorological data, GDD was estimated at each principle stage.

$$GDD = \sum_{k=0}^{n} n\left[\frac{Tmax + Tmin}{2}\right] - Tb$$

Where, Tmax is daily maximum temperature, Tmin is daily minimum temperature, Tb is base temperature (10 °C) and n is the number of days for specific growth stages.

A spearman rank correlation coefficient (r_s) was analyzed between rainfall, maximum and minimum temperature with leaf

Table 3
Phenological description of tree species of Temperate forests in Himalayan region.

a: Variation in phenophases recorded during 2019–21

Phenophase	*Q. leucotrichophora*			*R. arboreum*			*M. esculenta*		
	2019–20	2020–21	Delay/ Advance	2019–20	2020–21	Delay/ Advance	2019–20	2020–21	Delay/ Advance
Leaf initiation	Mar 3rd week	Apr 1st week	1 - week delay	Apr 3rd week	Apr 1st week	2 - week advance	May 4th week	Jun 1st week	1 - week delay
Flowering	Apr 1st week	Apr 4th week	3 - week delay	Feb 3rd week	Feb 4th week	1 - week delay	Aug 4th week	Sep 1st week	1 - week delay
Flower maturation	May 1st week	May 1st week	–	Mar 4th week	Mar 1st week	3 - week advance	Sep 2nd week	Sep 4th week	2 - week delay
Fruit setting	–	–	–	Sep 4th week	Sep 3rd week	1 - week advance	–	–	–
Fruit/acorn formation	Aug 3rd week	Sep 1st week	1 - week delay	Nov 4th week	Dec 1st week	1 - week delay	Apr 2nd week	Apr 1st week	1 - week advance
Fruit/acorn maturation	Dec 3rd week	Dec 1st week	2 - week advance	Jan 2nd week	Jan 1st week	3 - week advance	May 1st week	Apr 4th week	1 - week advance

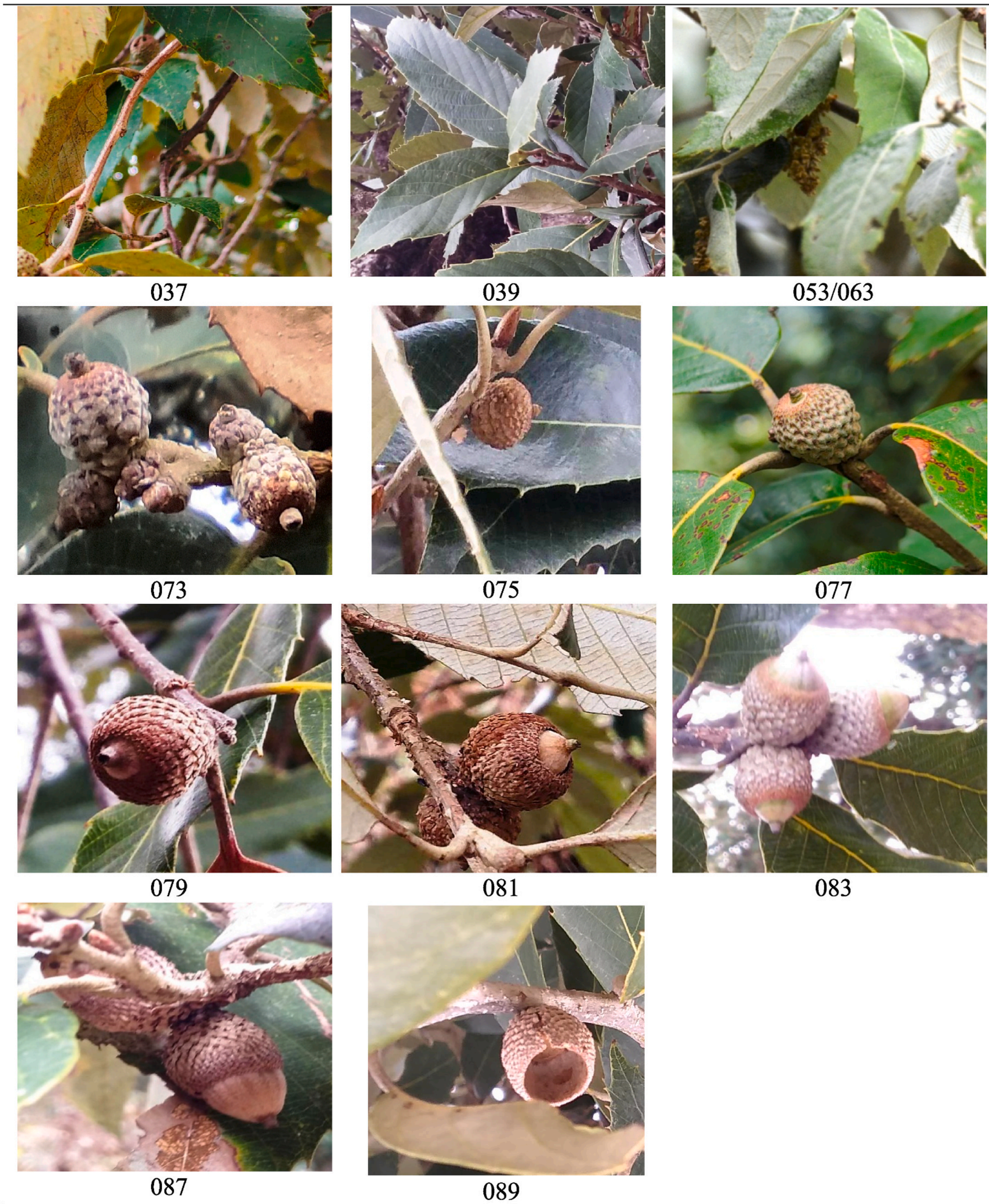
b: Comparison of phenological characteristics of the major tree species of Himalayan region with earlier studies

Leaf initiation	Flowering	Fruiting	Fruit ripening	Altitude	Rainfall	Temperature		Year	Source
						Min	Max		
Q. leucotrichophora									
Mar 3rd week	1st week Apr	Aug 3rd week	Dec 3rd week	1400–1980	1333	12.4	22.7	2019–21	2019–20
Apr 1st week	4th week Apr	Sep 1st week	Dec 1st week	1400–1980	1480	12.8	24.1		2020–21
Mar 1st week	1st week Apr	–	–	1761–2345	2258	4.6	25.9	–	Mittal et al., 2021
Feb 4th week	4th week Feb	April 2nd week	Nov 4th week	1700–1840	1589	−2.0	30.5	2008–09	Kumar et al., 2017
Mar 4th week	2nd week Mar	Apr 3rd week	Dec 1st week	–	–	–	–	1988	Negi, 1989
R. arboreum									
Apr 3rd week	Feb 3rd week	Nov 4th week	Mar 4th week	1400–1980	1333	12.4	22.7	2019–21	2019–20
Apr 1st week	Feb 4th week	Dec 1st week	Mar 1st week	1400–1980	1480	12.8	24.1		2020–21
Feb 2nd week	Jan 2nd week	Mar 2nd week	Oct 1st week	1700–1840	1589	−2.0	30.5	2008–09	Kumar et al., 2017
Apr 3rd week	Feb 4th week	Apr 1st week	Jun 1st week	–	–	–	–	1988	Negi, 1989
May	Feb	Jun	Oct	7–500	–	−2.4	25.5	2004–05	Paul et al., 2018
–	Jan 4th week	Apr 3rd week	–	–	1994	9	28	2018	Panta et al., 2019
M. esculenta									
May 4th week	Aug 4th week	Apr 2nd week	May 1st week	1400–1980	1333	12.4	22.7	2019–21	2019–20
Jun 1st week	Sep 1st week	Apr 1st week	Apr 4th week	1400–1980	1480	12.8	24.1		2020–21
Feb 4th week	Aug 2nd week	Apr 1st week	June 1st week	1700–1840	1589	−2.0	30.5	2008–09	Kumar et al., 2017
Apr 1st week	Aug 1st week	Mar 1st week	May 1st week	–	–	–	–	1988	Negi, 1989
Mar 4th week	Aug 1st week	–	–	1761–2345	2258	4.6	25.9	–	Mittal et al., 2021

initiation, flowering and fruiting with each studied species in two analyzed years 2019–20 and 2020-21 by using IBM SPSS.21.

4. Results

The detailed phenological growth stages of studied species were observed along with duration and heat unit requirement as growing degree days, which is used to estimate the growth and development of trees (Table 2). A total of 24 secondary growth stages were observed for *Q. leucotrichophora* (Fig. 2a), 28 for *R. arboreum* (Fig. 2b), and 24 for *M. esculenta* (Fig. 2c). Phenological descriptions of three studied species along with previous phenological observations were evaluated (Tables 3a and 3b).



b: *R. arboreum* with different phenophases and codes

Fig. 2b. Phenological growth stages of evergreen tree species of moist temperate forest in the study site of Uttarakhand. b: *R. arboreum* with different phenophases and codes.

4.1. Vegetative bud development (PGS 0)

Q. leucotrichophora produced a large number of leaf buds during winter rain (December to February) for 10–12 weeks and classified into three stages with 766.79 accumulated growing degree days (GDD) to complete stage (Table 2; Fig. 2a). The average annual rainfall during the time was varied from 0.46 to 3.08 mm with range of maximum temperature from 21.84 to 23.97 °C and minimum temperature from 2 to −1.82 °C. *R. arboreum* leaf bud starts during spring and dry summer (April to June) for 7–9 weeks and is characterized into five bud stages with 499.75 GDD to complete stage (Table 2; Fig. 2b). The average annual rainfall during the period was varied from 2.22 to 3.83 mm, with maximum temperature from 28.66 to 32.62 °C and minimum temperature from 8.58 to 15.64 °C.

Fig. 2c. Phenological growth stages of evergreen tree species of moist temperate forest in the study site of Uttarakhand. c: *M. esculenta* with different phenophases and codes.

4.2. Leaf development (PGS 1)

Q. leucotrichophora leaves flushes (branch with first leaves unfolded) occurred with the start of spring rain from March to June with six stages of leaf development (Table 2; Fig. 2a). The average annual rainfall, maximum temperature, and minimum were described in Fig. 4. Young leaves were densely pubescent and having silvery grey or pale pink color. Fully developed young leaves were distinguished from old leaves due to white or yellowish-white tomentum on the undersurface of leaves. *R. arboreum* leaves flushes occurred from April to July, having four growth stages of leaf development with 748.87 GDD to complete stage (Table 2; Fig. 2b). *R. arboreum* young leaves have light green color from both sides, whereas old leaves were dark green to brown hairs on the lower side. *M. esculenta*

c: *M. esculenta* with different phenophases and codes

Fig. 2d. Phenological growth stages of evergreen tree species of moist temperate forest in the study site of Uttarakhand.

leaves flushes occurred during dry summer to the start of winter (May to July), and had four growth stages of leaf development with 627.95 GDD to complete stage (Table 2; Fig. 2c). The color of *M. esculenta* young leaves was light green from both sides. Older leaves were pale green to dark green on the upper surface.

4.3. Shoot development (PGS 3)

Q. leucotrichophora young shoots appeared from April to June and attain full size within 10–12 weeks with 638.81 GDD to complete the stages of development (Table 2; Fig. 2a). *Q. leucotrichophora* young shoots were densely pubescent and silvery grey or pale pink in color. The dark grey color of the old shoots distinguished from young shoots. *R. arboreum* shoot development started from April to May to remains for 7–9 weeks with 413.33 GDD to complete the stage (Table 2; Fig. 2b). *R. arboreum* shoot was initially greenish, and with

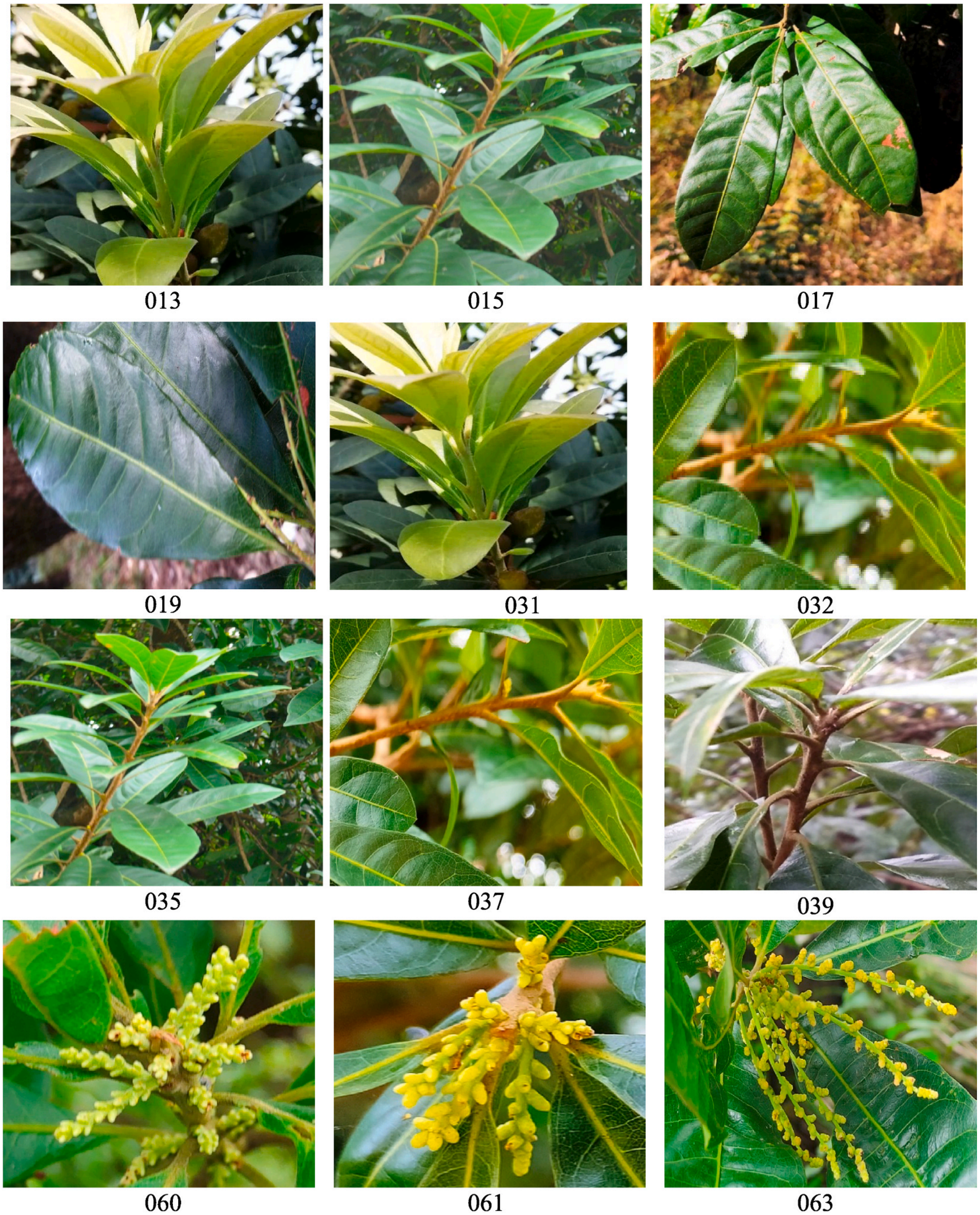


Fig. 2e. Phenological growth stages of evergreen tree species of moist temperate forest in the study site of Uttarakhand.

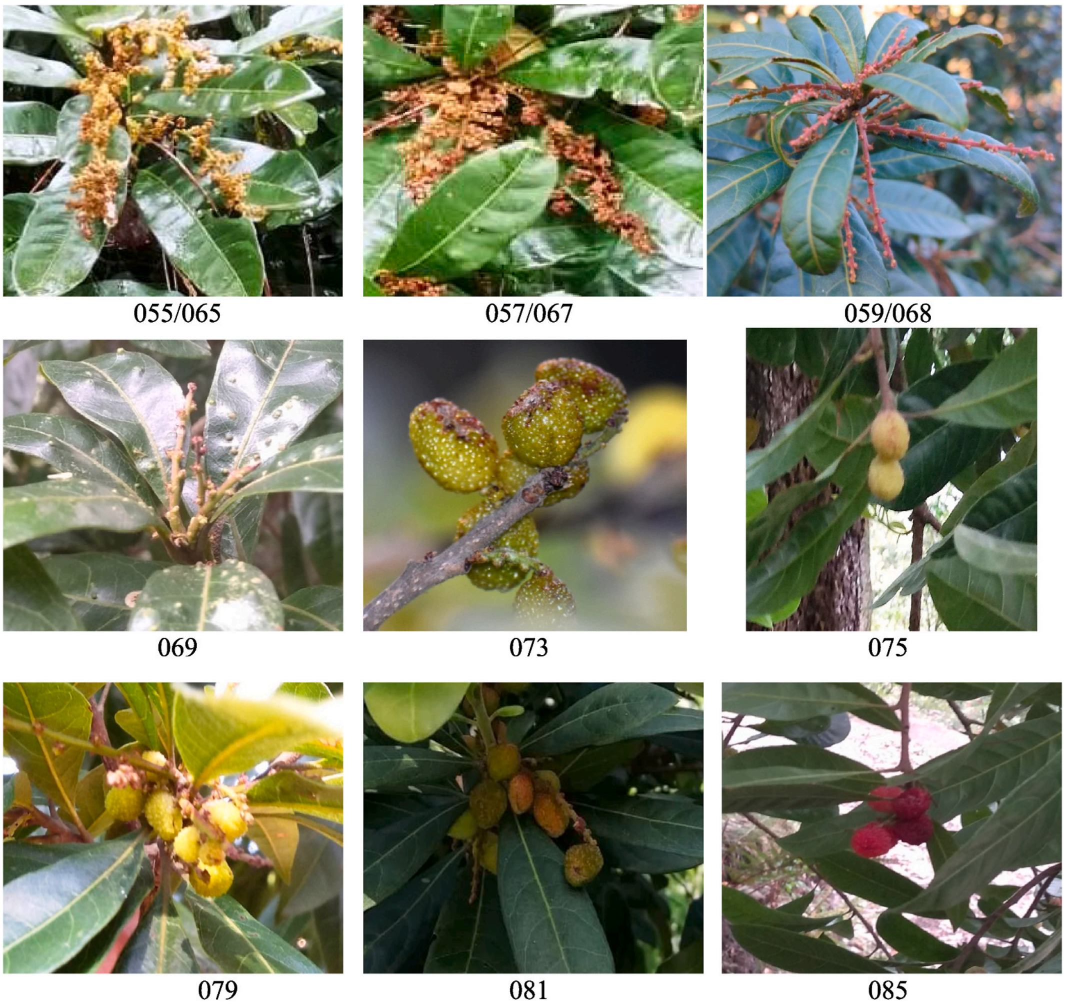


Fig. 2f. Phenological growth stages of evergreen tree species of moist temperate forest in the study site of Uttarakhand.

time become light reddish in color. *M. esculenta* young shoots appeared from May to June containing four growth stages to the complete stage (Table 2; Fig. 2c). *M. esculenta* young shoots were greenish and develop greyish color with time.

4.4. Inflorescence development (PGS 5)

Inflorescence of *Q. leucotrichophora* appeared during the summer season (April to May) and lasted 6–8 weeks with only one growth stage (Table 2; Fig. 2a). The inflorescence of *Q. leucotrichophora* began in the form of male (catkin) and female (pendulous). Pollination began after the catkin and pendulous ripened. The inflorescence of *R. arboreum* appeared between February and March and lasted 3–5 weeks, with four growth stages totaling 245.12 GDD (Table 2; Fig. 2b). *R. arboreum* inflorescence is called a corymb, and has a flattened top with an umbel-like structure. The inflorescence of *M. esculenta* appeared during the wet season (August to October) and lasted 3–5 weeks, with four growth stages (Table 2; Fig. 2c). Male florets were used to pollinate the species. Male florets typically had 2 to 16 stamens.

4.5. Flower development (PGS 6)

Q. leucotrichophora flowering appeared in the form of catkin from April to May and stayed for 6–8 weeks and has only one growth stage with 229.32 GDD to complete the stage (Table 2; Fig. 2a). During the time of flowering of *Q. leucotrichophora*, the rainfall was 2.22–2.67 mm with 8.56–12.43 °C and 28.66 to 35.01 °C minimum and maximum temperature, respectively (Fig. 4). Flowering of *R. arboreum* appeared during February and continued till March which persisted for 5–6 weeks and progressed in six growth stages with 251.09 GDD to complete stage (Table 2; Fig. 2b). During the time of flowering of *R. arboreum*, the rainfall was 1.39–4.17 mm with −1.51 to 1.73 °C and 23.97–24.73 °C minimum and maximum temperature, respectively (Fig. 4). *R. arboreum* flower was categorized as bell-shaped or tubular shape and borne in clusters generally called trusses. The flower generally had 5 petals fuse at the base with green calyx and 5 to 10 stamens. Flower development of *M. esculenta* appeared from August to October and remained for 5–8 weeks in seven growth stages with 374.49 GDD to the complete stage (Table 2; Fig. 2c). During the time of flowering of *M. esculenta*, rainfall was 10.66 to 1.5 mm with 18.34 to 9.9 °C and 28.62 to 26.5 °C minimum and maximum temperature, respectively (Fig. 4). Flower development and inflorescence development process were simultaneous in *R. arboreum* and *M. esculenta*.

4.6. Fruit development (PGS 7)

Fruit development in *Q. leucotrichophora* took place in the form of acorn (nut), generally grayish grey color, having conico-ovoid shape. Acorn emerged from August to December and remained for 16–19 weeks and contained four growth stages with 796.17 GDD to complete stage (Table 2; Fig. 2a). *R. arboreum* fruit development appeared in the form of oblong and curved capsules in greenish color with seeds having fimbriate tuft at the end. *R. arboreum* capsule formation begins in November and continues to December i.e., 2–3 weeks and contains two growth stages with 133.45 GDD to complete stage (Table 2; Fig. 2b). Fruit development of *M.* esculenta occurred in April and remained for 2–3 weeks and contained three growth stages with 125.18 GDD to complete stage (Table 2; Fig. 2c). The fruit of *M. esculenta* was a greenish color. Total rainfall received were 10.66 to 0.46 mm, 0.62 to 0.46 mm and 2.22 mm during fruit development of *Q. leucotrichophora*, *R. arboreum* and *M. esculenta,* respectively.

4.7. Fruit maturity (PGS 8)

Fruit maturation began after fruit development, and was characterized by a noticeable change in skin color. *Q. leucotrichophora* acorns ripened for 9–12 weeks from December to February and contained four growth stages with 456.27 GDD. (Table 2; Fig. 2a). *R. arboreum* fruit maturity occurred in December, with three growth stages with totaling 99.57 GDD (Table 2; Fig. 2b). The matured fruit of *R. arboreum* was brown. Further, capsules opened and shed the seeds, which remained open and stayed on the tree for several months. Fruit maturity of *M. esculenta* appeared in April and continued till May, and contained two growth stages with 111.03 GDD (Table 2; Fig. 2c). The ripened fruits were reddish dark.

4.8. Growth of foliar phenology

Marked seasonal variation was recorded in the phenophase pattern of three species (Tables 3a and 3b). Leaf flushing in all evergreen tree species was periodic, extended, and synchronous (Table 4). Leaf flushing in evergreen species was extended during springs (March to May) which are distinctly apparent in tree with light green color from distance. Leaf initiation period exhibited positive correlation ($p < 0.05$) with rainfall, and maximum and minimum temperature in 2019 and 2020 of study. However, *M. esculenta* tree species showed a negative correlation in 2021 (Table 5).

4.9. Growth of reproductive phenology

All the three species bloomed once in a year (i.e., annual frequency) and intermediate duration (1–5 months). Flowering duration varied from 55 to 65 days, 40–45 days and 30–35 days, respectively, in *Q. leucotrichophora*, *R. arboreum* and *M. esculenta* during study period. Amplitude of flower opening was medium in *Q. leucotrichophora* and *R. arboreum*, and high in *M. esculenta* (Table 4). Flowering duration of *R. arboreum* showed a significant positive correlation with minimum and maximum temperature but the correlation with rainfall was weakly positively correlated. Wheras, in *Q. leucotrichophora* the same was significantly positively correlated with rainfall and minimum temperature but very weakly negatively correlated ($r = 0.04$) with maximum temperature. *M. esculenta* flowering duration was significantly negatively correlated with minimum temperature and significantly positively correlated with rainfall during 2019–2021. However, the correlation with maximum temperature was insignificant (Table 5). All phenophases (i.e. leaf initiation, flowering and fruiting) were strongly influenced by the variation in minimum temperature in all species.

Duration of fruiting was periodic, extended and rapid (less than 4 months) in *R. arboreum* and *M. esculenta*, while it was periodic, extended and lengthy (more than 4 months) in *Q. leucotrichophora* (Table 4). Fruiting of *Q. leucotrichophora* and *R. arboreum* stared during mid of monsoon season (August to September) and the fruit matured during dry winter period after chilling dormant period (December to February). Fruit (Acorn) of *Q. leucotrichophora* was brown in color while *R. arboreum* having dust green in color. However, *M. esculenta* fruit appeared after winter rain shower (after February). Fruit of *M. esculenta* was green in color during

Table 4
Different phenophases of three species of temperate forest site of Uttarakhand.

Species	Phenological patterns			Flowering pattern			Synchrony	
	Leaf initiation	Flowering	Fruiting	Frequency	Duration	Amplitude	Flowering	Fruiting
Q. leucotrichophora	PeS	PeA	PeL	Annual	Intermediate	Medium	0.19	0.56
R. arboreum	PeS	PeA	PeR	Annual	Intermediate	Medium	0.31	0.55
M. esculenta	PeS	PeA	PeR	Annual	Intermediate	High	0.33	0.27

P=Periodic, **e** = extended periods more than 2 weeks, **S**=Synchronous, **A** = Asynchronous, **E** = evergreen, **R** = rapid fruit maturation less than 4 month, **L** = lengthy fruit maturation more than 4 month, **Frequency**=(the number of on/off cycle per year): annual (only one major cycle per year), **Duration**=(length of each cycle or phase): intermediate flowering (one to five months), **Amplitude**: intensity of quantity of flowering.

Table 5
Correlation between duration of phenophase with climatic parameters in moist temperate forest.

Phenophase	Spearman's rank correlation coefficient (r_s)					
	2019–20			2020–21		
	Min temp	Max temp	Rainfall	Min temp	Max temp	Rainfall
Q. leuchotrichophora						
Leaf initiation	0.86*	0.44*	0.48*	0.86*	−0.03	0.40*
Flowering	0.66*	−0.04*	0.54*	0.75*	0.24	0.001
Fruiting	−0.93*	−0.86*	−0.51*	−0.23*	−0.87*	−0.47*
R. arboreum						
Leaf initiation	0.79*	0.53*	0.25*	0.84*	−0.19	0.48*
Flowering	0.84*	0.70*	0.10	0.71*	0.69*	0.37*
Fruiting	−0.91*	−0.83*	−0.37*	−0.90*	−0.86*	−0.11
M. esculenta						
Leaf initiation	0.49*	−0.18	0.19	0.58*	−0.47*	0.44*
Flowering	−0.87*	0.14	0.81*	−0.87*	−0.49*	0.55*
Fruiting	0.70*	0.65*	−0.03	0.62*	0.24	0.29*

*$p < 0.05$.

immature stage while after it gives red or darkish color. Fruiting duration of *Q. leuchotrichophora* and *R. arboreum* showed a significant negative correlation to rainfall and temperature (minimum and maximum) while it was positive in *M. esculenta* (Table 5).

5. Discussion

The extended BBCH scale in studied species (*Q. leucotrichophora, R. arboreum* and *M. esculenta*) provided a holistic overview of specific vegetative and reproductive phenological stages of the species. The observed sequential progression of the major growth stages demonstrated that the reproductive growth was simultaneous with vegetative growth phases for all the three species (Figs. 3 and 5) with climatic variables (Fig. 4). Such developmental stages reflect that the developmental stages are strongly related to organ growth rates that may be attributed to the physiological processes underlying these stages, particularly hydraulics, biomechanics, and carbohydrate partitioning in plants.

Leaf flush was initiated during the spring season (Fig. 3). The variation in leaf emergence for the three species may be caused by the timing of leaf start, which depends upon the amount of rainfall during the months before to the spring season (i.e. January and February). Rain water restored in the soil and plant stem serve as primary cue for initial vegetative development after the dormancy period [33] and later compensated by the rainfall. The leaf flush in *Q. leucotrichophora* was reported during 4th week of February by Ref. [34] and 1st week of March by Ref. [35] in Uttarakhand, however, in *R. arboreum* it was reported during the 2nd week of February [34] in Uttarakhand and during May [36] in Arunachal Pradesh. In *M. esculenta*, leaf flush was reported during 4th week of February by Ref. [34] and 4th week of March by Ref. [35] in Uttarakhand (Table 3b). Changes in leaf flushing are related to spatio-temporal variation leading to altered environmental conditions such as rainfall and temperature, soil moisture, and plant water status [37]. Moreover, the climatic variables (average monthly rainfall, minimum and maximum temperature) of the study sites (Fig. 4) was different from the other study sites (Fig. 3b) might be the reason for variation in leaf initiation timing in different sites. However, species distinctions in leaf initiation timing assist to protect tissues and leaves from late frost, a strategy commonly used by Himalayan temperate tree species that are sensitive to temperature, frost, and moisture regime [35]. Photoperiod could be another factor for regulating the leaf emerging in species [38] as *Q. leucotrichophora* (ring-porous) having a large vessel, which affect the timing of leaf initiation [39].

Peak flowering duration was approximately 36, 42 and 56 days in present study for *Q. leucotrichophora*, *R. arboreum* and *M. esculenta,* respectively. *Q. leucotrichophora* and *R. arboreum* flowered during springs while *M. esculenta* flowered during monsoon season, which may be due to the variation in seasonal rainfall and temperature. Variability in flowering phase of the species might be due to their adaptation strategies towards temperate conditions that are favorable for growth throughout the year [40]. Variation in flowering pattern among tree species are primarily due to their adaptive mechanisms to climatic conditions [32]. Flowering in *Q. leucotrichophora* started during 4th week of February [35] and 1st week of April [34] in Uttarakhand, however, *R. arboreum* flowering started during 1st week of February [34] in Uttarakhand and February [36] in Arunachal Pradesh, and for *M. esculenta* it starts during1st and 2nd week of August [34,36] in Uttarakhand (Table 3b). In Himalayan region, rainfall has been reported to more strongly regulate the phenological events (i.e. flowering duration) than temperature and photoperiod. However, in the present study, flowering

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Q. leucotrichophora	○○○○	○○○		İ	İ İİİ▪▪	İ İİ İ▪^^	İ İİİ	◊◊	◊◊◊◊	◊◊◊◊	◊◊◊◊	◊◊◊◊
R. arboreum	○○○○	▪▪▪○○	▪▪▪▪^	İ İ İ^^^	İ İİİ	İ İ			∘∘∘∘	∘∘∘∘	∘∘∘"	""""○◊◊◊
M. esculenta					◊◊◊○	İ○○○	İ İİİ	İ İİİ	▪	▪▪^^	^	

Leaf initiation	İ	Fruit maturation	○	Fruit	◊	Capsule formation	"	Flower maturation	^	Flowering	▪	Fruit set	∘

Fig. 3. Pheno-gram of flowering, fruiting and leaf initiation phenology of three evergreen species in moist temperate forest Uttarakhand.

Climatic variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average monthly Precipitation (mm)	3.08	1.39	4.17	2.22	2.67	3.83	12.78	10.66	1.5	0	0.62	0.46
Minimum Temperature (^{0}C)	-1.82	-1.51	1.73	8.58	12.43	15.64	17.73	18.34	13.69	9.9	4.74	2
Maximum Temperature (^{0}C)	18.13	23.97	24.73	28.66	35.01	32.62	30.67	28.62	27.75	26.5	22.9	21.84

Fig. 4. Climatic data of average monthly precipitation, minimum and maximum temperature of study site.

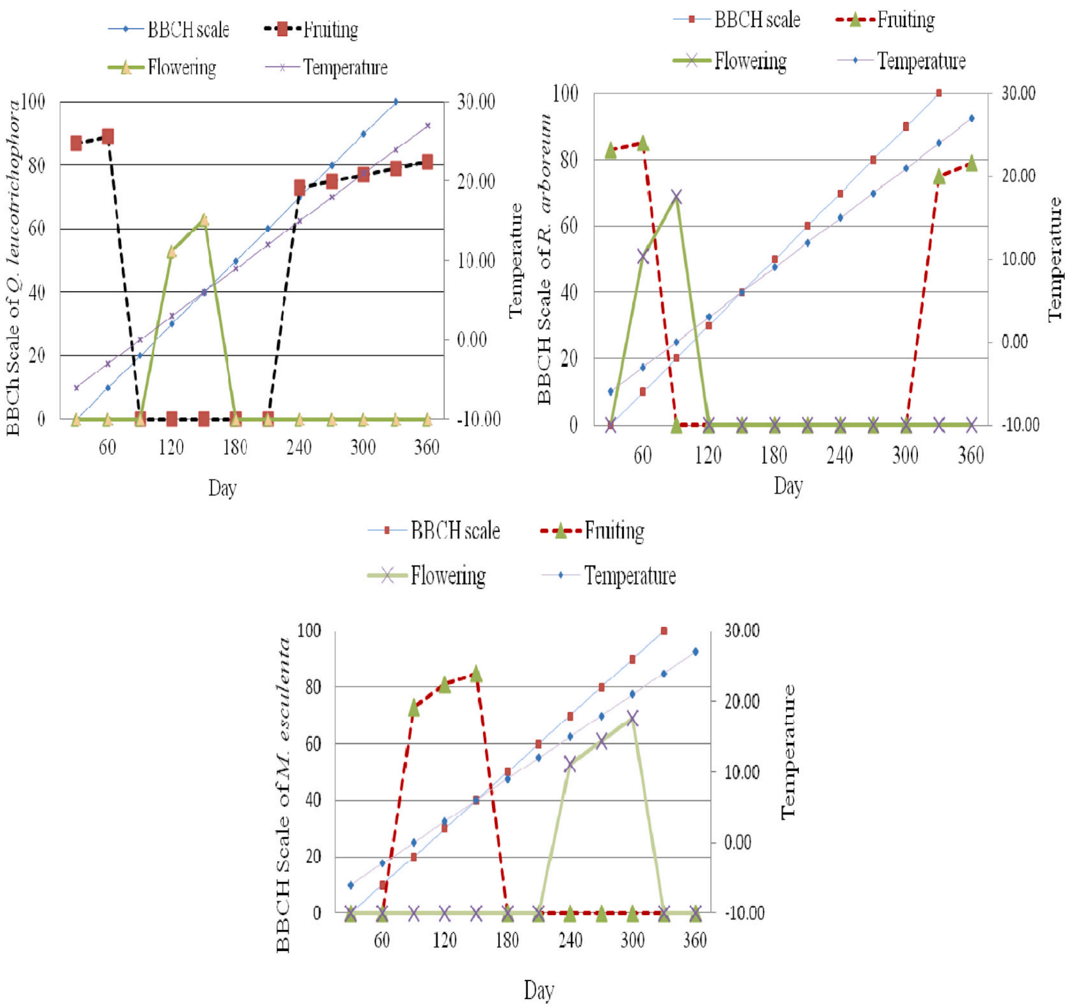


Fig. 5. Reproductive phases of the three species.

duration was more strongly influenced by the changes in minimum temperature compared to maximum temperature and rainfall (Table 5). Strong relations of phenological variations altered with climate at large spatial scale as a result of changing habitat conditions in temperate forest trees are likely to have strong implication on forest management in future. Therefore, understanding the plant adaptation strategies and formulating forest management strategies would be essential for the conservation of climate sensitive temperate tree species in Himalaya.

Annual variation in flowering phenology was observed within the population in all examined species to varying degrees of magnitude (Fig. 3). Medium levels of flower synchrony are exhibited by *M. esculenta* as a means of outcrossing required tree species for increased reproductive fitness as the characteristic determine the outcrossing by requiring pollinators to travel between distantly positioned individuals in a population [41]. Generally, high blooming synchrony in a plant community is essential for cross-pollination and reproductive output in the form of fruit and seed set. Flowering plasticity and varied topography assist to prolong flowering time, which is essential for maintaining pollinator variety [42].

Fruit development of *Q. leucotrichophora* and *R. arboreum* occurred during the monsoon season (Fig. 3), and fruit maturity happened during a dry spell of the winter season. However, *M. esculenta* fruiting occurred from January to February. Flowering longetivity of *Q.*

leucotrichophora is lengthy while *R. arboreum* and *M. esculenta* are rapid. Variation in longevity of fruiting might be due to species' behavior and their interaction with the environment as well as depend upon resource utilization strategy, with earlier shoot emergence and flowering time related to bigger plant size and lower reproductive effort in earlier periods [43].

Phenological variations in *Q. leucotrichophora* and two other species with earlier reports were possibly related to adaptive mechanisms acquired by the species to cope up with altered abiotic variables on a large spatial scale due to changes in habitat conditions (Table 3b). The correlation analysis between climatic parameters and phenophases was significant with minimum temperature for all species, however, it was not consistent for maximum temperature and rainfall in the two years (Table 5). The consistently strong correlations of all phenophases in three species with minimum temperature indicate that phenological variations in the species in this region is triggered by the changes in minimum temperature rather than rainfall and maximum temperature. The response of flowering duration in threes species varied strongly in relation to climatic factors (i.e. min and max temperature and rainfall). For example, it was strongly related to either minimum and maxaximum temperature as in *R. arboreum* or minimum temperature and rainfall as in *Q. leucotrichophora* and *M. esculenta*. Therefore, changes in minimum temperature as a result of future climate change in association with other variables may strongly influence the reproductive potential of these species. Further, it will affect the ecological performance of these species and their ability to provide goods and services to the local inhabitants.

Overall descriptive phenology of *Q. leucotrichophora*, *R. arboreum* and *M. esculenta* varied with climatic conditions with some degree of flowering asynchrony across individuals. The information may assist in understanding the genetical, physiological, ecological, and evolutionary behavior of these species, and may develop a guideline for future mechanistic management of these species. *Q. leucotrichophora* leaf initiation and flowering showed a strong correlation with rainfall and temperature which reflect the adaptability towards the local environment condition that might be the reason for the dominance of the species in the present forest site. Moreover, variations in phenologic areal stages are an adaptive strategy of species such as minimizing the risk of frost damage by optimization of growing season length with variation in phenology in tree species [44] besides functioning of tree species in temperate forests [45,46] and playing for mitigative role for climate change [47].

6. Conclusion

The phenological observations based on the BBCH scale for three tree species suggest a consistent consensus-based strategy to identify phenophases in relation to climate. Close matches between the vegetative growth stages and reproductive growth stages demonstrated that the reproductive growth stage was simultaneous with vegetative growth phases for all the three species (Figs. 3 and 5). Moreover, phenological monitoring of species allow the establishment of study models to determine and predict the physiological and morphological response that plant have developed to the changing environment over evolutionary history. Contrary to the earlier reports, this study suggests that minimum temperature serves as a proximal cue for the changes in tree phenology of temperate forest rather than rainfall. Further, phenological variations in temperate forest trees are related to altered climate variables at large spatial scale due to changing habitat conditions. Precisely, the observed variation in phenological stages is crucial for understanding the plant adaptation strategies and to formulate forest management strategies. Moreover, the information will assist in understanding how tree species will respond to future climate change. Such phenological researches are crucial for global change studies for future modeling and also for conservation biology.

Author contribution statement

Rajat Singh: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Rajiv Pandey: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Monika Rawat: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Tara Chand: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Srikant Tripathi: Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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References

[1] H. Wang, D. Liu, H. Lin, A. Montenegro, X. Zhu, NDVI and vegetation phenology dynamics under the influence of sunshine duration on the Tibetan plateau, Int. J. Climatol. 35 (2015) 687–698, https://doi.org/10.1002/joc.4013.

[2] A. Paul, M.L. Khan, A.K. Das, Phenological characteristics of Rhododendron species in temperate mixed broad-leaved forests of arunachal Himalaya, India, J. Forest and Environ. Sci. 34 (2018) 435–450, https://doi.org/10.7747/JFES.2018.34.6.435.

[3] A.A. Hoffmann, C.M. Sgro, Climate change and evolutionary adaptation, Nature 470 (2011) 479–485, https://doi.org/10.1038/nature09670.

[4] T.H. Sparks, A. Menzel, N.Chr Stenseth, European cooperation in plant phenology, Clim. Res. 39 (2009) 175–177. https://www.jstor.org/stable/24870435 (accessed December 3, 2022).

[5] J. Trunschke, J. Stocklin, Plasticity of flower longevity in alpine plants is increased in populations from high elevation compared to low elevation populations, Alpine Bot. 127 (2017) 41–51, https://doi.org/10.1007/s00035-016-0176-4. C. Körner, D. Basler, Phenology Under Global Warming, Science. (2010). htttps://doi.org/10.1126/science.1186473.

[6] R.A. Montgomery, K.E. Rice, A. Stefanski, R.L. Rich, P.B. Reich, Phenological responses of temperate and boreal trees to warming depend on ambient spring temperatures, leaf habit, and geographic range, Proc. Natl. Acad. Sci. USA 117 (2020) 10397–10405, https://doi.org/10.1073/pnas.1917508117.

[7] N. Gcs, P. Singh, S. Pratap Singh, Atmospheric warming-associated phenological earliness does not increase the length of growing season in himalayan trees, For. Sci. 67 (2021), https://doi.org/10.1093/forsci/fxab040.

[8] M.D. Schwartz, R. Ahas, A. Aasa, Onset of spring starting earlier across the Northern Hemisphere, Global Change Biol. 12 (2006) 343–351, https://doi.org/10.1111/j.1365-2486.2005.01097.x.

[9] F.S. Gilliam, Forest ecosystems of temperate climatic regions: from ancient use to climate change, New Phytol. 212 (2016) 871–887, https://doi.org/10.1111/nph.14255.

[10] D.W. Inouye, B. Barr, K.B. Armitage, B.D. Inouye, Climate change is affecting altitudinal migrants and hibernating species, Proc. Natl. Acad. Sci. U. S. A. 97 (2000) 1630–1633, https://doi.org/10.1073/pnas.97.4.1630.

[11] C. Both, S. Bouwhuis, K. Lessells, M. Visser, Climate change and population declines in a long-distance migrant, Nature 441 (2006) 81–83, https://doi.org/10.1038/nature04539.

[12] J. Morisette, A. Richardson, A. Knapp, E. Graham, J. Abnatzoglou, B. Wilson, D. Breshears, G. Henebry, J. Hanes, L. Liang, Tracking the rhythm of the seasons in the face of global change: phenological research in the 21 st century, Front. Ecol. Environ. - Front Ecol Environ 7 (2009) 253–260, https://doi.org/10.1890/070217.

[13] C. Ammer, Diversity and forest productivity in a changing climate, New Phytol. 221 (2019) 50–66, https://doi.org/10.1111/nph.15263.

[14] B.J. Stucky, R. Guralnick, J. Deck, E.G. Denny, K. Bolmgren, R. Walls, The plant phenology ontology: a new informatics resource for large-scale integration of plant phenology data, Front. Plant Sci. 9 (2018). https://www.frontiersin.org/article/10.3389/fpls.2018.00517 (accessed January 14, 2022).

[15] C.M. Zohner, B.M. Benito, J.-C. Svenning, S.S. Renner, Day length unlikely to constrain climate-driven shifts in leaf-out times of northern woody plants, Nat. Clim. Change 6 (2016) 1120–1123, https://doi.org/10.1038/nclimate3138.

[16] C.M. Zohner, B.M. Benito, J.D. Fridley, J.-C. Svenning, S.S. Renner, Spring predictability explains different leaf-out strategies in the woody floras of North America, Europe and East Asia, Ecol. Lett. 20 (2017) 452–460, https://doi.org/10.1111/ele.12746.

[17] S. Gugger, H. Kesselring, J. Stocklin, E. Hamann, Lower plasticity exhibited by high- versus mid-elevation species in their phenological responses to manipulated temperature and drought, Ann. Bot. 116 (2015) 953–962, https://doi.org/10.1093/aob/mcv155.

[18] S. Piao, Q. Liu, A. Chen, I.A. Janssens, Y. Fu, J. Dai, L. Liu, X. Lian, M. Shen, X. Zhu, Plant phenology and global climate change: current progresses and challenges, Global Change Biol. 25 (2019) 1922–1940, https://doi.org/10.1111/gcb.14619.

[19] C. Korner, The use of 'altitude' in ecological research, Trends Ecol. Evol. 22 (2007) 569–574, https://doi.org/10.1016/j.tree.2007.09.006.

[20] A. Ahmad, M.U. Rehman, A.F. Wali, H.A. El-Serehy, F.A. Al-Misned, S.N. Maodaa, H.M. Aljawdah, T.M. Mir, P. Ahmad, Box–behnken response surface design of polysaccharide extraction from Rhododendron arboreum and the evaluation of its antioxidant potential, Molecules 25 (2020) 3835, https://doi.org/10.3390/molecules25173835.

[21] V. Lefebvre, C. Villemant, C. Fontaine, C. Daugeron, Altitudinal, temporal and trophic partitioning of flower-visitors in Alpine communities, Sci. Rep. 8 (2018) 4706, https://doi.org/10.1038/s41598-018-23210-y.

[22] P.D. Lancashire, H. Bleiholder, T.V.D. Boom, P. Langeluddeke, R. Stauss, E. Weber, A. Witzenberger, A uniform decimal code for growth stages of crops and weeds, Ann. Appl. Biol. 119 (1991) 561–601, https://doi.org/10.1111/j.1744-7348.1991.tb04895.x.

[23] J.J. Martinez-Nicolas, P. Legua, P. Melgarejo, R. Martinez, F. Hernandez, Phenological growth stages of nashi tree (Pyrus pyrifolia): codification and description according to the BBCH scale, Ann. Appl. Biol. 168 (2016) 255–263, https://doi.org/10.1111/aab.12261.

[24] S. Rajan, D. Tiwari, om Singh, P. Saxena, S. Singh, N. Reddy, K.K. Upreti, M. Burondkar, A. Bhagwan, R. Kennedy, Application of extended BBCH Scale for phenological studies in mango (Mangifera indica L.), J. Appl. Hortic. 13 (2011) 72–78, https://doi.org/10.37855/jah.2011.v13i02.25.

[25] K. Kishore, Phenological growth stages and heat unit requirement of Indian blackberry (Syzygium cumini L., Skeels), Sci. Hortic. 249 (2019) 455–460, https://doi.org/10.1016/j.scienta.2019.02.032.

[26] S. Gautam, K. Bawa, Widespread climate change in the himalayas and associated changes in local ecosystems, PLoS One 7 (2012), e36741, https://doi.org/10.1371/journal.pone.0036741.

[27] S. Saha, G. Rajwar, M. Kumar, Soil properties along altitudinal gradient in Himalayan temperate forest of Garhwal region, Acta Ecol. Sin. 38 (2018) 1–8, https://doi.org/10.1016/j.chnaes.2017.02.003.

[28] V. Singh, R. Thadani, A. Tewari, J. Ram, Human influence on banj oak (Quercus leucotrichophora, A. Camus) forests of central Himalaya, J. Sustain. For. 33 (2014) 373–386, https://doi.org/10.1080/10549811.2014.899500.

[29] H. Krishna, B.L. Attri, A. Kumar, Improvised Rhododendron squash: processing effects on antioxidant composition and organoleptic attributes, J. Food Sci. Technol. 51 (2014) 3404–3410, https://doi.org/10.1007/s13197-012-0855-0.

[30] A. Kabra, R. Sharma, S. Singla, R. Kabra, U.S. Baghel, Pharmacognostic characterization of Myrica esculenta leaves, J. Ayurveda Integr. Med. 10 (2019) 18–24, https://doi.org/10.1016/j.jaim.2017.07.012.

[31] J.j. Martinez-Nicolas, P. Legua, P. Melgarejo, R. Martinez, F. Hernandez, Phenological growth stages of nashi tree (Pyrus pyrifolia): codification and description according to the BBCH scale, Ann. Appl. Biol. 168 (2016) 255–263, https://doi.org/10.1111/aab.12261.

[32] M. Ahmad, S.K. Uniyal, D.R. Batish, S. Rathee, P. Sharma, H.P. Singh, Flower phenological events and duration pattern is influenced by temperature and elevation in Dhauladhar mountain range of Lesser Himalaya, Ecol. Indicat. 129 (2021), 107902, https://doi.org/10.1016/j.ecolind.2021.107902.

[33] A. Das, N. Linthoingambi Devi, D. Singha, Phenology of Deciduous Tree Species in Traditional Meitei Homegardens of Barak Valley, Assam, Northeast India, 2019, https://doi.org/10.22271/tpr.2019.v6.i3.046.

[34] J. Gao, K. Wang, X. Zhang, Patterns and drivers of community specific leaf area in China, Global Ecol. Conserv. 33 (2022), e01971, https://doi.org/10.1016/j.gecco.2021.e01971.

[35] S. Kumar, N. Chopra, A.R.M.S. Al-Tawaha, Phenological variations in tree and shrub species of a banj oak (Quercus leucotrichophora A. Camus) dominated forest in Kumaun, Central Himalaya, Adv. Environ. Biol. 11 (2017) 35–44. https://go.gale.com/ps/i.do?p=AONE&sw=w&issn=19950756&v=2.1&it=r&id=GALE%7CA499696214&sid=googleScholar&linkaccess=abs (accessed January 4, 2022).

[36] A. Mittal, A. Tewari, N. Singh, S. Sharma, Patterns of phenological characteristics of important tree species of kumaun Himalaya, Curr. World Environ. 16 (2021), https://doi.org/10.12944/CWE.16.1.15.

[37] A. Paul, M.L. Khan, A.K. Das, Phenological characteristics of Rhododendron species in temperate mixed broad-leaved forests of arunachal Himalaya, India, J. Forest and Environ. Sci. 34 (2018) 435–450, https://doi.org/10.7747/JFES.2018.34.6.435.

[38] C. Barbaroux, N. Breda, Contrasting distribution and seasonal dynamics of carbohydrate reserves in stem wood of adult ring-porous sessile oak and diffuse-porous beech trees, Tree Physiol. 22 (2002) 1201–1210, https://doi.org/10.1093/treephys/22.17.1201.

[39] L. Ghelardini, A. Santini, S. Black-Samuelsson, T. Myking, M. Falusi, Bud dormancy release in elm (Ulmus spp.) clones–a case study of photoperiod and temperature responses, Tree Physiol. 30 (2010) 264–274, https://doi.org/10.1093/treephys/tpp110.
[40] D. Tiwari, om Singh, P. Saxena, S. Singh, N. Reddy, K.K. Upreti, M. Burondkar, A. Bhagwan, R. Kennedy, Application of extended BBCH Scale for phenological studies in mango (Mangifera indica L.), J. Appl. Hortic. 13 (2011) 72–78, https://doi.org/10.37855/jah.2011.v13i02.25.
[41] K.S. Gaira, R.S. Rawal, B. Rawat, I.D. Bhatt, Impact of climate change on the flowering of Rhododendron arboreum in central Himalaya, India, Curr. Sci. 106 (2014) 1735–1738. https://www.jstor.org/stable/24103010 (accessed February 24, 2023).
[42] R.G. Sharp, M.A. Else, R.W. Cameron, W.J. Davies, Water deficits promote flowering in Rhododendron via regulation of pre and post initiation development, Sci. Hortic. 120 (2009) 511–517. https://www.cabdirect.org/cabdirect/abstract/20093127306 (accessed February 4, 2022).
[43] S. Chandra, A. Singh, J.R. Mathew, C.P. Singh, M.R. Pandya, B.K. Bhattacharya, H. Solanki, M.C. Nautiyal, R. Joshi, Phenocam observed flowering anomaly of Rhododendron arboreum Sm. in Himalaya: a climate change impact perspective, Environ. Monit. Assess. 194 (2022) 877, https://doi.org/10.1007/s10661-022-10466-1.
[[44]] E. Bustamante, A. Burquez, Effects of plant size and weather on the flowering phenology of the organ pipe cactus (stenocereus thurberi), Ann. Bot. 102 (2008) 1019–1030, https://doi.org/10.1093/aob/mcn194.
[45] K. Kramer, B. Degen, J. Buschbom, T. Hickler, W. Thuiller, M.T. Sykes, W. de Winter, Modelling exploration of the future of European beech (Fagus sylvatica L.) under climate change—range, abundance, genetic diversity and adaptive response, For. Ecol. Manag. 259 (2010) 2213–2222, https://doi.org/10.1016/j.foreco.2009.12.023.
[46] R. Singh, M. Rawat, R. Pandey, Quantifying leaf-trait co-variation and strategies for ecosystem functioning of Banj Oak forest in Himalaya, Ecol. Indicat. 150 (2023), https://doi.org/10.1016/j.ecolind.2023.110212.
[47] J. Kishwan, R. Pandey, V.K. Dadhwal, Emission removal capability of India's forest and tree cover, Small Scale Forestry 11 (1) (2012) 61–72.