CHAPTER 2
REVIEW OF LITERATURE

2.1 Vegetation of Himalayan region

2.1.1 Origin

The Himalayas were formed as a result of the collision between the Indian plate and the Eurasian plate approximately 55 to 50 million years ago. The process persisted until 40 million years ago, resulting in the subduction of a section of the Indian plate under the Asian plate and the uplift of Tethyan deposits, which ultimately led to the development of the Himalaya [1]. Initially, the collision between the two tectonic plates led to the development of a contiguous landmass for the three regions, viz., the Indian Peninsula, the Sino-Japanese region, and the Malayan Archipelago, and served as the ‘intercontinental biological highway’ [2,3]. As the climatic conditions of the newly formed Himalayan landscape were tropical, the first wave of migration was characterized by colonization of the region with taxa bearing tropical affinities. Taxa from different parts of the world, such as Alangiaceae, Anacardiaceae, Bombacaceae, Dipterocarpaceae, Malvaceae, and others, were able to grow freely in the Himalayas because there were no physical or climatic barriers [1,4,5]. The first wave of migration of plant taxa lasted approximately for a period of 30 million years and ceased with the rise of the Himalayan Mountain range [1,6]. The upliftment of the Himalayan Mountain range resulted in the formation of physical barriers that disrupted the initial land connections, developed the Southwest monsoon system, and subsequently led to varied climatic conditions ranging from tropical to alpine [1,6,7]. As the climate changed after the upliftment, plants like *Acer, Anemone, Betula, Clematis, Desmodium, Fagonia, Ranunculus, Trifolium*, and others moved through the northwest part of the Himalaya in a second wave [1, 5]. These plants came from nearby areas in Europe, North Asia, Russia, Siberia, and other places.

Plants from different families, like Arecaceae, Brassicaceae, Fabaceae, Lamiaceae, Liliaceae, and others displaying tropical affinities represents the composition of the Paleocene flora in the Eastern Himalayas [4,8]. Scientists have studied palaeobotanical and palynoflora from sediments from the Paleocene to the Oligocene in parts of the Eastern Himalaya. They found many families of plants that usually live in tropical or subtropical climates. This supports Lakhanpal's [9] claim that tropical plants dominated the Indian subcontinent during the Paleogene period [4]. According to Du's [10] study, the Himalayan region was characterized by the presence of deciduous vegetation during the Neogene period, with the Miocene flora of the Eastern Himalayan region accounting for a significant portion of the tropical deciduous trees [4]. Singh and Sarkar [4] say that the Miocene flora is mostly made up of plants from the tropical to subtropical regions. These include *Albizia, Anisoptera, Duabanga, Dipterocarpus, Lagerstroemia, Sterculia,* and *Terminalia*, among others. The enrichment of the Miocene vegetation with species such as *Dillenia, Ficus, Rhododendron*, etc., from the Southeast Asian and the Sino-Japanese regions indicates the influx of tropical families [4,11]. As the monsoon emerged during the Oligocene-Miocene epochs, with the Indian monsoon estimated to be 15-20 million years old, parts of the Eastern Himalayan region witnessed the establishment of species like *Dipterocarpus, Elaeocarpus, Shorea, Sterculia*, etc. during the middle to late Miocene epoch [4,7,11]. Many changes in the geomorphic and climate in the Eastern Himalayas and nearby areas created physical barriers that restricted genes from moving between populations. This caused plant families to become more diverse through speciation during the Oligocene and Miocene periods [1,3,6,11]. Therefore, the modern vegetation of the Eastern Himalayan region is formed through the immigration of floras from the adjacent region and evolutionary changes of the Neogene floras. These forests are predominantly composed of *Artocarpus, Bombax, Duabanga, Sterculia, Syzygium, Terminalia, Zizyphus*, and other species that are still prevalent throughout Northeast India [4].

2.1.2 Types of vegetation in the Indian Himalayan Region

The vegetation of India is an evolutionary remnant of the old-world vegetation, shaped by the fusion of different elements, i.e., Southeast Asian-Malaysian, Chinese-Japanese, Tibetan, Euro-Siberian, and Arctic-Alpine, following the India-Eurasia plate collision. Prehistoric vegetation evolved over different geological timescales, under varied geomorphological and climatic aspects, resulting in a mosaic distribution of different forest types in India [12]. In 1936, Sir H.G. Champion attempted to classify and compile the various types of forest present in India in his work "Preliminary Survey of Forest Type of India and Burma" [13]. This work was later revised by Sir H.G. Champion and S.K. Seth through the incorporation of several factors like climate, locality factors, altitudes, species composition, etc., and in 1968 'A Revised Survey of the Forest Type of India' was published [14]. Table 2.1 presents the classification of forest types of India referring preliminary and revised survey of forest type of India.

Table 2.1 Classification of forest types of India

Champion (1936)	Champion and Seth (1968)
1. Tropical Forests	1. Moist Tropical Forests
1.1. Wet evergreen forests	1.1. Tropical Wet Evergreen Forests
1.2. Semi-evergreen forests	1.2. Tropical Semi-evergreen Forests
1.3. Moist deciduous forests	1.3. Tropical Moist Deciduous Forests
1.4. Littoral and swamp forests	1.4. Littoral and Swamp Forests
1.5. Dry deciduous forests	
1.6. Thorn forests	
1.7. Dry evergreen forests	
2. Montane Subtropical Forests	2. Dry Tropical Forests
2.1. Subtropical broadleaved hill forests	2.1. Tropical Dry Deciduous Forests
2.2. Subtropical pine forests	2.2. Tropical Thorn Forests
2.3. Subtropical dry evergreen forests	2.3. Tropical Dry Evergreen Forests
3. Montane Temperate Forests	3. Montane Subtropical Forests
3.1. Montane wet temperate forests	3.1. Subtropical Broadleaved Hill Forests
3.2. Himalayan moist temperate forests	3.2. Subtropical Pine Forests
3.3. Himalayan dry temperate forests	3.3. Subtropical Dry Evergreen Forests
4. Sub-alpine Forests	4. Montane Temperate Forests
4.1. Sub-alpine forests	4.1. Montane Wet Temperate Forests
	4.2. Himalayan Moist Temperate Forests
	4.3. Himalayan Dry Temperate Forests
5. Alpine Scrub	5. Sub-alpine Forests
5.1. Moist alpine scrub	5.1. Sub-alpine Forests
5.2. Dry alpine scrub	
	6. Sub-alpine Forests
	6.1. Sub-alpine forest
	7. Alpine Scrub
	7.1. Moist Alpine Scrub
	7.2. Dry Alpine Scrub

The Indian Himalayan Region [15] observes mosaic patterns of various vegetation types, identified by different groups, subgroups, and categories according to Champion and Seth's [14] classification, due to significant variations in altitudes and climatic conditions. Therefore, Singh and Singh identified the vegetation of the Himalaya into 11 formation types (Table 2.2).

Table 2.2 Formation-types of the Himalayan vegetation [15]

Sl. No.	Formation-type	Distribution
1	Submontane broadleaf ombrophilous forest	It is restricted within the Eastern Himalaya, below 1000 m. The majority of the annual rainfall occurs during the period of May-September.
2	Submontane seasonal broadleaf forest	It is present in parts of the Eastern and Central Himalaya characterized by an annual rainfall of 1000-1400 mm and a period of 4-5 months with rainfall <50 mm.
3	Submontane broadleaf summer-deciduous forest	It is distributed in parts of the Western Himalaya characterized by skeletal soil and nutrient-poor dry sites.
4	Low-montane needle-leaf forest with concentrated summer leaf-drop	It is restricted between 1000-1800 m along the Himalaya (except Kashmir).
5	Low-montane sclerophyllous evergreen broadleaf forest	It is limited to the parts of the Western Himalaya characterized by weak monsoon.
6	Mid-montane broadleaf ombrophilous forest	It is confined between 1500-3000 m in the Eastern Himalaya with an annual rainfall >2000 mm and mean annual temperature ranging between 11-18°C.

7	Low to mid-montane hemisclerophyllous broadleaf forest with concentrated summer leaf-drop	It is distributed between 1500-3000 m in the Western and Central Himalaya with an annual rainfall between 1000-2500 mm and a mean annual temperature ranging between 13-16°C.
8	Mid-montane needle-leaf evergreen forest	It is distributed between 1700-3000 m in the Eastern and Western Himalaya with its habitat can vary from mesic to xeric conditions
9	Mid-montane winter-deciduous forest	It has limited distribution in the stream-traversed areas of the region dominated by mid-montane hemisclerophyllous and needle-leaf evergreen forests.
10	High-montane mixed stunted forest	It is distributed in parts of the Eastern, Western and Central Himalaya with an altitude of >3000 m where the melting of snow forms the primary source of water.
11	Very high-montane scrub	It is confined to the higher altitudes of the Himalayas (3500-4900 m).

Bahuguna et al. [12] highlighted that the descriptions used by Champion and Seth to define the subgroups were not the climax vegetation, but rather reflections of site-specific local factors. Therefore, Bahuguna et al. [12] incorporated climatic parameters such as rainfall and temperature along with latitude to classify the forest types of India into 10 major groups and 44 subgroups. Later, this classification was further revised by Singh et al. [16] with the inclusion of other factors like ecological, biogeographic, and edaphic conditions to broadly classify the forests present in the Indian Himalayan Region into tropical forests, tropical moist deciduous forests, subtropical forests, temperate forests, and alpine forests.

2.2 Phenology

2.2.1 History

The term "phenology," first proposed by Belgian botanist Charles François Antoinne Morren in 1853, originates from the Greek word "phaino," meaning to show, to bring to light, or to appear [17,18]. Despite coining the term in the middle of the 19th century, the practice of observing the seasonality in various life cycle events of plants and animals has deep historical roots, dating back to the ancient Egyptian, Mesopotamian, and Asian civilizations [19]. Generally, the ancient records of phenological observations were primarily linked to cultural and economic aspects, including agricultural practices. These associations are evident in the findings of well-written records and narratives of phenological events, such as the 8th-century BCE phenological calendar, the Chinese Classic of Poetry (Shijing) from 1000 BCE, and the Fan Shengzhi Book from 32 BCE–100 CE in China [17,18]. Similarly, the recording of flowering dates for cherry trees in Tokyo, Japan, from the 9th century until the present, forming a crucial aspect of the cherry blossom festival, highlights the cultural significance of the phenological observations [17,18]. Beyond Asia, similar utilization of phenological observations for agricultural practices is exemplified by several historical documents, such as the works of Roman historian Marcus Porcius Cato (234–149 BCE) in his book On Agriculture and the ripening dates of grapes in different parts of Europe, such as Pinot Noir grapes from 1370 CE up to the present in Burgundy and Swiss grape harvest records dating back to 1480 CE. [18,20,21].

Piao et al. [22] categorize the history of phenology into three distinct periods. The first period (around 10th century BCE to 17th century CE) is defined by the use of phenological observations to determine the seasonality of the occurrence of life cycle events of plants and animals for various agricultural practices [22]. The second period (17th century CE to 1990s) was defined by the development of terminologies, observation techniques, networks, and statistical tools [22,23]. The 18th century CE marked the second period with several landmark moments of phenological studies, including the initiation of "Indications of Spring" by Robert Marsham in 1736, England, which spanned over 200 and documented the vegetative as well as reproductive cycles of many species, and "Philosophia Botanica" by Carolus Linnaeus in 1751, which outlined methods for the compilation of phenological observations along with climatic conditions "so as to show how areas differ" [17,18,24]. Andrew Hopkins proposed the bioclimatic law during this period, emphasizing the role of latitude, longitude, and altitude in determining climatic conditions and revising our understanding of plant phenology and its relationship to climate [25]. The third period (1990s to present) was defined by the rapid development of sophisticated phenological events monitoring systems and statistical models [23]. The studies are focused more on understanding phenological events as responses to the impacts of anthropogenic-induced climate [22]. The establishment of phenological networks and advancement in remote sensing in the few preceding decades has facilitated and expanded the range of phenological studies from the local to the global level, thereby adding new dimensions to the existing knowledge [22].

2.2.2 Phenology and Climate

The phenological events are species-specific responses to variations in environmental conditions. Any alterations in the climatic conditions of an area can exert visible impacts such as alteration in the timing of the occurrences of phenophases [26,27]. According to Fenner [28], phenological events follow distinct patterns in regions with highly seasonal climatic conditions. More than one climatic variable governs the onset of phenophases, but the climatic variable that predominantly affects phenophases is site-specific [28,29,30,31].

Temperature changes predominantly influence phenophases in mid and high latitudes [32]. Several studies have observed that in the temperate zone, an increase in air temperature has subsequently led to advancement in the onset of phenophases at the rate of a few days per decade [32,33,34,35]. As plant species tend to undergo a period of dormancy during the winter, any increase in temperature in the post-dormancy period influences the vegetative development [32]. However, in regions where snowfall occurs, the occurrence of snowmelt regulates the onset of phenophases and the growing season [36,37,26,38]. This is because the water generated by snowmelt, along with a change in temperature, also acts as a trigger for the initiation of leaves [39]. However, both the quantity of snow and thermal energy [26] regulate the snowmelt date, suggesting the subtle role of precipitation, temperature, and other climatic variables like insolation in regulating phenological events. Bjorkman et al. [26] assert that snowmelt influences the flowering phenophases of early-flowering plants, while an increase in spring temperature influences the flowering phenophases of late-flowering plants. Körner and Basler [40], Chen et al. [39], and Zohner et al. [41] reported that some plants require a distinct period of winter chilling, which acts as a cue for the onset of spring phenophases like bud burst. Morin et al. [42] found that while an increase in temperature accelerated leaf initiation, it negatively correlated with leaf unfolding. In cold-winter regions, an increase in temperature as a consequence of climate change may cause an inadequate chilling period, which may subsequently delay the onset of spring phenophases [43,44,45]. However, in areas of higher latitudes experiencing severe winter, variations in photoperiod also serve as cues for the release of bud dormancy, leading to budburst, along with the onset of phenophases such as leaf senescence [46,47,48,49].

Climate variables such as photoperiod, temperature, and rainfall also cue phenophases like leaf onset and leaf fall in lower latitudes [50, 51]. In places where photoperiod stays mostly the same throughout the year, however, temperature and rainfall can be used to predict when phenological events of plant growth will happen [29, 30, 31, 52, 53]. Many studies [54, 55, 56, 57, 58, 59] have reported that precipitation acts as a predominant cue for phenological events in the tropical zone. Rainfall extensively influences phenophases like leaf initiation and leaf fall in the tropical zone, where water availability has distinct effects on leaf development [55, 60]. This is because leaf initiation and leaf abscission are adaptation techniques of vegetation to the water stress caused by a periodic dry spell as well as a decrease in temperature [48]. The dry season's leaf abscissions enable the plant shoots to reduce water stress and maintain their turgidity [61, 62, 63]. The occurrence of rainfall subsequent to a dry spell replenishes the soil moisture and allows rehydration of the stems, thereby facilitating the onset of several phenophases like leaf flush, flowering, and fruiting [59, 52, 64, 65, 66].

However, even in tropical regions, plants respond differently to climatic variations through their phenophases, with some studies observing that leaf initiation occurs before the onset of precipitation [62, 67, 68]. Bhat and Murali [69], Bhat [66], and Prabhakaran [70] have observed that changes in temperature and photoperiod also trigger the onset of phenophases, such as leaf flush during the dry pre-monsoon period and leaf abscission during the post-monsoon period in the tropical zone. Besides temperature and rainfall, a few studies [58, 71] have also found that photoperiod serve as a trigger for reproductive phenophases in the tropical zone, even though variation in photoperiod is less there than in the temperate zone. However, the adaptation of the plant's reproductive cycles to long-term climatic averages may cause such an association [58]. A comparative analysis of phenological studies in different parts of Northeast India is given in Table 2.3, Fig. 2.1 and Fig. 2.2.

Table 2.3 Phenological studies conducted in different parts of Northeast India

Study area	Observation method	Findings	References
Arunachal Pradesh	Ground-based	The phenophases of *Rhododendron* sp. are sequential and cued by the prevailing climatic conditions of the area.	Paul et al. [72]
Arunachal Pradesh	Remote sensing	The alpine tree line ecotone displayed an extension of growing season and upward shift.	Mohapatra et al. [73]
Assam	Ground-based	The deciduous traits of trees are a response to the availability of water.	Devi and Garkoti [74]
Assam	Ground-based	Rainfall and temperature act as cues for the phenophases and tend to influence the shifts in the occurrence of phenophases of some species.	Das and Das [75]
Assam	Ground-based	Variations in the occurrence of phenophases of different species enables the optimum use of the available resources.	Devi and Garkoti [76]
Assam	Ground-based	*Vatica lanceaefolia* has distinct seasonal phenophases and the growth of the plants are positively associated with rainfall.	Borah and Devi [77]
Assam	Ground-based	The deciduous traits of trees enable optimal use of available resources and reduce competition.	Devi et al. [78]
Assam	Ground-based	The vegetative and reproductive phenology of *Barringtonia acutangula* is cued by temperature, rainfall as well as aridity index.	Nath et al. [79]

Assam	Ground-based	The occurrence of vegetative and reproductive phenophases of *Aquilaria malaccensis* are predominantly determined by rainfall and temperature.	Borogayary et al. [80]
Assam	Remote sensing	Compared to rainfall, temperature plays significant role in determining the occurrence of phenophases and subsequent growth of the plants.	Deka et al. [81]
Assam	Ground-based	The phenophases of the deciduous trees are sensitive to variations in rainfall patterns.	Devi et al. [82]
Assam	Ground-based	The phenophases of *Parkia timoriana* are influenced by climatic factors specifically temperature and rainfall.	Devi et al. [83]
Manipur	Ground-based	The phenophases display seasonality with the occurrences coinciding with seasonal transitions of climatic conditions.	Kikim and Yadava [84]
Meghalaya	Ground-based	The occurrence phenophases of plants are species-specific with an assemblage of discrete patterns for a balanced ecosystem function.	Shukla and Ramakrishnan [85]
Meghalaya	Ground-based	The vegetative as well as reproductive phenophases are driven by rainfall and moisture availability.	Pao et al. [86]
Meghalaya	Remote sensing	The NDVI of vegetation is associated with temperature and rainfall.	Bhuyan et al. [87]

Mizoram	Ground-based	The reproductive phenophases of Lagerstroemia speciosa display variability.	Khanduri [88]
Mizoram	Ground-based	The leaf phenophases of sub-tropical forests are cued by climatic variables.	Lalruatfela and Tripathi [89]
Mizoram	Ground-based	Shifts in the occurrences of phenophases were observed highlighting the impact of changes in climatic conditions on the phenophases.	Singh and Sahoo [90]
Mizoram	Ground-based	The flowering phenophases of *Rhododendrum arboreum* are influenced by altitude-induced atmospheric and soil surface temperature.	Malsawmkima and Sahoo [91]
Mizoram	Ground-based	Photoperiod and minimum temperature were found to be correlated with the occurrences of phenophases.	Devi et al. [92]
Mizoram	Ground-based	The correlation of phenophases with climatic variables was species-specific.	Kumar et al. [93]
Mizoram	Remote sensing	Rainfall is the predominant factor determining the forest growth.	Chanda et al. [94]
Sikkim	Ground-based	The occurrences of reproductive phenophases of *Oroxylum indicum* is predominantly determined by temperature and relative humidity.	Sharma et al. [95]
Sikkim	Ground-based	The leaf traits of Rhododendron are influenced by altitudes, phenology durations and phylogeny.	Basnett and Devi [96]

Sikkim	Remote sensing	The treelines display upward shifting accompanied with an expansion of growing season and advancement in the start and end of growing season	Singh et al. [97]

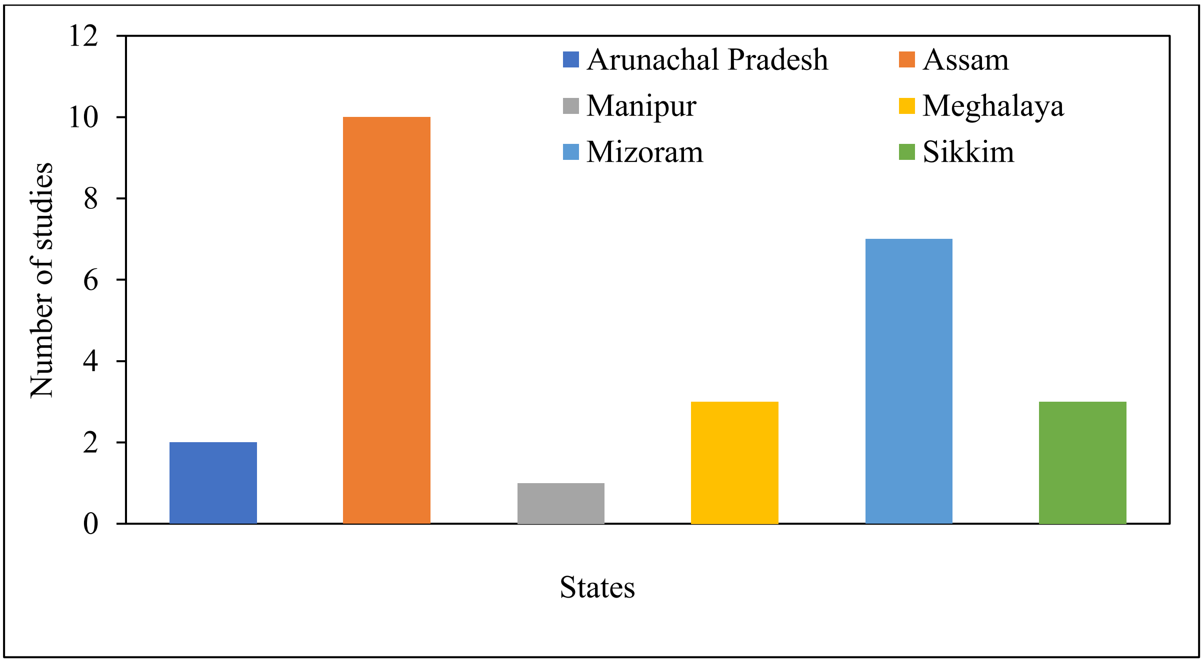

Fig. 2.1 Graphical representation of the number of phenological studies conducted in different states of Northeast India

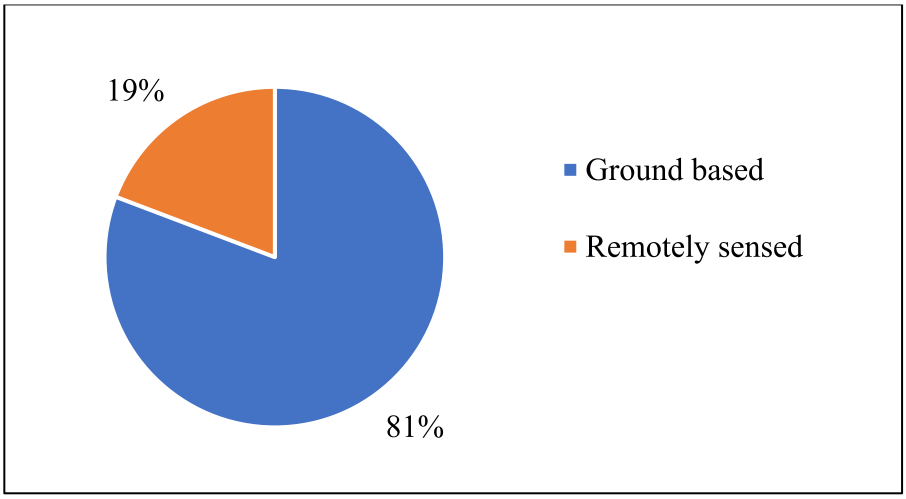

Fig. 2.2 Graphical representation of different methods used for phenological studies in Northeast India

2.3 Himalayan soil

2.3.1 Soil formation and nutrient dynamics

Multiple determinants, such as parent material, climate, and vegetation cover, condition the time-controlled process of soil formation [98]. Orographic features such as location and elevation influence the weathering process of parent materials, which primarily leads to soil development in mountainous regions like the Himalaya. This process intensifies as altitude decreases [98, 99, 100]. The variations in temperature and monsoonal rainfall across the Himalaya often lead to the truncation of regoliths and significantly affect the process of both weathering and erosion across different regions [98, 101]. As a result, the physicochemical properties of soil tend to vary due to the combined effects and interactions among various soil-forming factors [102, 103, 104]. In addition to the parent material and the weather, the plants that grow in that area have a big impact on the soil's physicochemical properties through litter and other plant debris. This is why changes in vegetation can be seen in the soil [98, 104, 105]. Liu et al. [106] noted in a meta-analysis study that taproots tend to have more organic carbon content and nutrient availability in the rhizosphere zone compared to fibrous roots, highlighting the effects of root systems on the edaphic properties of an area.

Research has well documented how the addition of organic matter affects the physicochemical as well as biological properties of soil [107, 108, 109, 110]. Researchers have observed that the presence of organic carbon positively impacts the chemical properties of the soil by releasing and making nutrients available [111, 112, 113, 114, 115]. Another property of soil that varies with changes in climatic parameters and the density of forest cover is soil moisture [116]. According to studies conducted by Bargali et al. [102, 117], Yamashita et al. [118], and Xu et al. [119], soil moisture plays a critical role in the decomposition of plant litter, leading to subsequent alterations in the soil pH and availability of nutrients and thereby predominantly influencing the physiological traits of forest ecosystems. Additionally, the amount of soil moisture, along with free ions, also affects the electrical conductivity (EC) of soil, highlighting the impact of soil moisture on the physicochemical properties of soil [120]. Thus, the development of forest soil from the simultaneous evolution of vegetation and soil through natural succession imparts specific physicochemical characteristics, which may vary depending on the quantity, type, and windfall mosaic structure of vegetation present in the area [104, 105, 121, 122, 123, 124].

2.4 Phenological models

2.4.1 Development of phenological models

René-Antoine Ferchault de Réaumur, in 1735, initiated phenological modeling by summarizing the relationships between phenophase occurrences and environmental temperatures in the thermic summation model [17, 125]. Adanson (1750) further modified Réaumur's phenological model by incorporating the thermal threshold concept, which excludes temperatures below 0°C from the summations [17]. Initially designed to understand the relationship between phenophases and temperature, phenological models have evolved into indispensable tools for establishing "phenology-climate" relations and assessing the ecological impact of climate change over the past several decades [17, 126]. Therefore, according to Chuine [127], the phenological modeling consists of four stages: defining the models, collecting the data, adjusting the model to the data, and hypothesis testing. Essentially, Chuine [127] classifies the phenological data collection, which forms one of the initial stages of phenological modeling, into four types of observations: (i) the population of trees in their natural or planted habitats, (ii) similar plants under different environmental conditions, (iii) greenhouse experiments, and (iv) the quantification of pollen released in the atmosphere.

2.4.2 Types of phenological models

According to Chuine et al. [125] and Zhao et al. [126], the phenological models can be broadly classified into three types:

- Theoretical models: These models are based on cost/benefit trade-offs between the occurrence of a phenophase and the acquisition of resources in an optimal manner [17, 126]. The purpose of making theoretical models is to understand how phenophases like leaf production change over time and how they happen rather than how they change from year to year [125, 126].
- Statistical models: These models are also known as empirical plant phenology models [126]. These statistical models are made to find links between when phenophases happen and environmental factors, but they don't include specific biological processes [125, 126]. These models often vary in complexity, and statistical fitting methods are implemented to obtain the models' parameters [126].
- Mechanistic models: The mechanistic models, also known as dynamic phenology models, are built on the relationships of different biological and/or physiological

processes with the driving environmental variables [126]. The data required for the mechanistic models are primarily obtained by observations of the "assumed cause-effect relationships," while the models' parameters are estimated by experimental methods and statistical fittings [125, 126].

However, there are still problems with getting a clear picture of how plant phenology and climate are connected, which makes all models less useful [126]. Moreover, the phenological models are often region-specific, thereby limiting their applicability and efficiency across different geographical locations [127]. Thus, with the lack of phenological models specific to the subtropical and tropical regions, the applications of statistical approaches tend to improve the understanding of responses of plants in terms of the occurrences of phenophases to the changes in the climatic conditions [126, 127].

2.5 References

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