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RESEARCH ARTICLE

Butterflies Under a Changing Climate: From Physiological Responses to Community Restructuring and Conservation Challenges

Dr. Revathy V. S.[1]* and Dr. George Mathew[2]
[1]Assistant Professor, Research and Postgraduate Department of Zoology, Union Christian College (Autonomous), Aluva, Kerala, India
Email: revathyvs@uccollege.edu.in
ORCID: 0009-0005-4458-0814

[2]Scientist (Rtd), Kerala Forest Research Institute, Kerala, India

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Abstract

Butterflies are sensitive components of terrestrial ecosystems and respond to climatic variation through changes in development, survival, phenology, dispersal, reproduction and species interactions. This narrative review synthesises evidence on climate-driven changes in butterfly populations and communities, emphasising the mechanisms linking climatic drivers to physiological responses, phenological shifts, geographic redistribution, community restructuring and conservation outcomes. The review follows a documented search, screening and classification procedure. Each source is classified by region, taxon and evidence tier, so that long-term studies from temperate Europe and North America are used as mechanistic benchmarks and hypotheses for the Western Ghats of India rather than as direct evidence of change there. Where studies concern particular taxa, the species and family are named, and the Western Ghats fauna is considered by

its five major families (Papilionidae, Pieridae, Nymphalidae, Lycaenidae and Hesperiidae). Temperate-region studies show earlier seasonal activity and poleward or elevational redistribution in many species, but these responses are not universal: multivoltine and mobile species may track climatic conditions more effectively, whereas specialists, sedentary species and range-restricted endemics may face greater constraints. For the Western Ghats, direct evidence of climate-driven change in butterflies is currently very limited. Available data consist mainly of inventories, short-term seasonal surveys and studies of monsoon-linked migration in danaine Nymphalidae, which identify climate-sensitive processes but not long-term trends. The review identifies the lack of standardised long-term tropical datasets as a major limitation and recommends taxon-resolved monitoring across elevation, habitat and seasons. Climate change also acts within a broader threat matrix that includes habitat fragmentation, pesticides and other pollutants, which may reduce the capacity of populations to track climatic change. Conservation should therefore combine habitat connectivity, microclimatic refugia, host-plant management, climate-smart reserve design and long-term monitoring.

Keywords: Climate change; lepidoptera; phenology; range shifts; community restructuring; Western Ghats; habitat specialisation; conservation

1. Introduction

Butterflies are among the most intensively monitored insect groups and are widely used as indicators of environmental change because their ectothermic physiology, short generation times and close associations with plants make them responsive to changes in temperature, precipitation and habitat conditions. Climate change can affect butterflies at several organisational levels: temperature alters development and adult activity; precipitation modifies host plants and nectar resources; changing seasons shift emergence and reproduction; and altered climatic suitability redistributes species geographically. These processes can ultimately change population abundance, community composition and extinction risk.

Long-term studies provide compelling evidence that climate change is associated with biological changes in butterflies. Poleward shifts of European butterfly ranges have been associated with regional warming (Parmesan et al., 1999), while long-term monitoring has documented advances in seasonal activity (Roy & Sparks, 2000). A globally coherent climate-change signal has also been demonstrated across natural systems (Parmesan & Yohe, 2003). However, these findings do not imply a universal response. Species differ in thermal tolerance, dispersal ability, host-plant dependence, voltinism and habitat requirements, while landscapes differ in connectivity and resource availability.

A major limitation of a purely descriptive review is that observations such as earlier emergence, range expansion or population decline are listed without explaining how they are connect-

ed. Earlier emergence is not necessarily beneficial: its demographic effect depends on whether host plants and nectar resources change at compatible rates. Likewise, a climatically suitable area may remain inaccessible when habitat is fragmented. Climate exposure must therefore be interpreted together with ecological traits and landscape context (Hill et al., 1999; Thomas et al., 2001).

This issue is particularly important in tropical biodiversity hotspots. The Western Ghats support high butterfly diversity and endemism, including species associated with specialised montane and evergreen-forest habitats (Kunte, 2008; Padhye et al., 2012). Recent work has documented substantial butterfly diversity and seasonal dynamics in the coastal and foothill landscapes of the central Western Ghats (Naik et al., 2022), but long-term standardised datasets capable of separating climate effects from land-use and seasonal variation remain limited. This review therefore asks: (i) through which mechanisms do climate change affect butterflies; (ii) why do species respond differently; (iii) how do species-level responses translate into community restructuring; and (iv) what conservation strategies can maintain butterfly diversity under continued climatic change? Throughout, the review asks how far each answer is supported by evidence from the Western Ghats itself.

2. Review Methodology

2.1 Review Design and Questions

This is a narrative review rather than a systematic review or meta-analysis. A narrative design was chosen because the available studies differ widely in taxa, regions, climatic variables and methods, and cannot be combined statistically. To limit selection bias, the questions (Section 1), search terms, eligibility criteria and classification scheme described below were applied consistently to all sources and are reported so that the process can be repeated.

2.2 Literature Search

Searches were run in Web of Science Core Collection, Scopus and Google Scholar databases for publications from 1995 to 2025. Because much of the Western Ghats butterfly literature appears in regional journals, searches were extended to the *Journal of Threatened Taxa*, *Current Science*, the *Journal of the Bombay Natural History Society* and the *Journal of Insect Conservation*, and the reference lists of key papers were screened for further records. The core search string, adapted to the syntax of each database, was: (butterfl* OR Lepidoptera OR Rhopalocera OR Papilionidae OR Pieridae OR Nymphalidae OR Lycaenidae OR Hesperiidae) AND (climat* OR warming OR temperature OR rainfall OR monsoon OR drought OR phenolog* OR “range shift*” OR elevation*).

A regional string was then added: ("Western Ghats" OR Sahyadri OR "peninsular India" OR Kerala OR Karnataka OR "Tamil Nadu" OR Maharashtra OR Goa OR India OR "South Asia") (Table 1).

Studies were included if they (i) reported data on butterflies (Rhopalocera); (ii) addressed climatic variables, seasonality, phenology, distribution, elevation or community composition, or addressed a non-climatic stressor that interacts with climate effects; and (iii) were published in English in peer-reviewed journals. Published faunal surveys and checklists from the Western Ghats were included as baseline evidence even when climate was not analysed, because they define which taxa occur where. Studies of moths and other organisms were not treated as evidence for butterflies and are cited only where explicitly labelled as non-butterfly context. Conference abstracts, theses, preprints and press reports were not used as evidence; they served only to locate primary publications. Titles and abstracts were screened first, followed by full-text assessment of potentially relevant papers.

Table 1. *Evidence Tiers Used in This Review and Their Role in the Synthesis*

Tier	Source region and taxa	Role in this review	Examples cited
1	Butterfly studies from the Western Ghats and peninsular India (inventories, seasonal surveys, migration studies)	Baseline for taxa, endemism and climate-sensitive processes in the region of focus; not evidence of long-term climate trends unless repeated sampling is reported	Kunte (2005); Padhye et al. (2012); Naik et al. (2022)
2	Global or other tropical butterfly analyses	Comparative context for tropical responses and for migratory species	Chowdhury et al. (2021a, 2021b)
3	Long-term or resurvey studies of butterflies in temperate Europe and North America	Source of mechanisms and hypotheses; transferability to the Western Ghats is evaluated in Section 12.4	Parmesan et al. (1999); Roy & Sparks (2000); Wilson et al. (2007); Forister et al. (2010); Rödder et al. (2021)
4	Non-butterfly taxa or laboratory systems (moths, birds, Drosophila)	Context only; not used to support butterfly-specific claims	Macgregor et al. (2019); Manna et al. (2024); Kwak et al. (2021)

3. Climate Change as an Interacting Driver

Climate change should be understood as a chain of interacting processes rather than as a single variable. Temperature and precipitation affect individual physiology directly, but their ecological consequences are mediated by resource availability, species interactions and landscape structure. A useful framework is climatic exposure → physiological response → phenological response →

altered resource interactions → demographic change → range redistribution → community turnover. Each step may amplify or buffer the preceding response.

For example, warming can accelerate larval development and potentially permit an additional generation in a multivoltine species. That apparent benefit may disappear if drought reduces host-plant quality or adult nectar resources. Similarly, an upslope shift may not secure persistence if the receiving habitat lacks host plants or is isolated. Microclimate is also important because vegetation structure can buffer extreme temperatures and create fine-scale refugia that are not captured by regional averages (Suggitt et al., 2011).

4. Physiological Responses to Temperature and Precipitation

4.1 Temperature

As ectotherms, butterflies depend strongly on environmental temperature. Moderate warming can accelerate larval development and extend periods suitable for adult activity. Such changes may increase the number of generations in multivoltine species. Trait-based analyses of butterfly records indicate that voltinism and other life-history traits help explain interspecific differences in responses to warming (Diamond et al., 2011, using North American butterfly records), although the direction of the effect varies among species and regions.

The same warming can become harmful when temperatures approach upper physiological limits. Heat waves may cause mortality at egg and larval stages, reduce adult activity and increase water loss. Consequently, the temperature–fitness relationship is nonlinear. Mean annual temperature alone cannot adequately predict vulnerability because short extreme events may produce disproportionate mortality. Long-term British moth data (non-butterfly evidence, Tier 4) fluctuated strongly between years, and the authors suggested that extreme weather events may contribute to such fluctuations (Macgregor et al., 2019).

4.2 Precipitation and Drought

Precipitation affects butterflies through water balance, vegetation growth and resource availability. Drought can reduce nectar production and host-plant quality, whereas prolonged rainfall can restrict flight and increase disease risk. In monsoon-dependent tropical systems, the timing and variability of rainfall may be more informative than annual totals. In peninsular India the monsoon is a recognised driver of butterfly seasonality and movement: southern Indian danaine butterflies (*Tirumala* and *Euploea*, Nymphalidae) migrate between the Western Ghats and the eastern plains in a pattern linked to the south-west monsoon (Kunte, 2005; Bhaumik & Kunte, 2017; see Section 12.2), and climatic-niche models for 405 migratory butterfly species worldwide show strong seasonal switching in habitat suitability (Chowdhury et al., 2021b).

Temperature and precipitation should therefore be analysed jointly. A warm season with adequate rainfall may increase productivity, while similar warming combined with drought may reduce population growth. Future butterfly monitoring should incorporate multiple climatic variables and extreme events rather than relying on temperature alone.

5. Phenology and Ecological Mismatch

Earlier seasonal activity is one of the clearest documented biological responses to warming. Studies of British butterflies (Roy & Sparks, 2000) and of butterflies in the north-west Mediterranean Basin (Stefanescu et al., 2003) have reported advancement of seasonal phenology in association with warmer conditions. No equivalent long-term phenological series for Western Ghats butterflies was identified in the searches for this review (Section 12). Earlier activity can extend the flight season, but the ecological outcome depends on synchronisation with resources and interacting organisms.

Host plants are especially important because larvae often depend on specific plant species or developmental stages. If butterfly breeding advances faster than host-plant phenology, larvae may encounter unsuitable or nutritionally inferior foliage. Conversely, if plants advance faster, suitable resources may be missed. Phenological mismatch can therefore reduce recruitment even when the butterfly itself responds rapidly to warming (Visser & Gienapp, 2019).

However, phenological differences should not automatically be interpreted as mismatch. Behavioural or developmental plasticity, altered host use and local adaptation may partially compensate for the mismatch. Species traits help explain variation in phenological sensitivity (Diamond et al., 2011; North American butterfly records). The crucial question is whether the timing of butterfly development remains compatible with the resources required for population growth.

6. Host Plants, Predators and Ecological Interactions

Butterfly responses cannot be understood independently of plants. Host-plant distribution determines where larvae can develop, while nectar plants influence adult survival and reproduction. Climate-driven plant range shifts may therefore constrain butterfly range expansion even where temperature becomes suitable. Conversely, new plant–butterfly associations may emerge as distributions change. Temperature-dependent changes in host use have been shown to contribute to rapid range expansion in butterflies (Pateman et al., 2012; for the brown argus *Aricia agestis*, Lycaenidae, in Britain). In the Western Ghats, about 320 butterfly species are recorded using roughly 834 plant species or groups from 88 families as larval hosts (Nitin et al., 2018), so host-plant responses to climate are likely to be central to butterfly outcomes there, but they remain unstudied.

Predators, parasitoids and competitors may also respond to climate at different rates. Consequently, a population response attributed to temperature may partly result from changes in trophic interactions. Climate effects are therefore often indirect as well as direct, and population studies should distinguish these pathways where possible (Boggs & Inouye, 2012; for the mormon fritillary *Speyeria mormonia*, Nymphalidae, in Colorado, USA).

7. Climate Change, Habitat Loss and Multiple Stressors

Climate change operates within a broader threat matrix. Habitat fragmentation can prevent populations from tracking suitable climates, while pesticides can reduce survival and reproductive performance. Forister et al. (2010), using a 35-year dataset of butterflies in north-central California, USA, demonstrated compounded effects of climate change and habitat alteration on butterfly diversity. This finding is important because climatic tolerance does not guarantee persistence if habitat is unavailable or inaccessible.

Pesticides represent a well-established additional pressure; their effects on butterflies include direct toxicity and indirect effects through host plants and food webs (Braak et al., 2018). This review also considered heavy metals and microplastics. There is direct evidence for toxic effects of metals in butterflies: zinc exposure has been associated with increased mortality and altered antioxidant gene expression in laboratory-reared monarch butterflies (*Danaus plexippus*, Nymphalidae) with low dietary macronutrient access (Shephard et al., 2022), while nickel exposure has produced transgenerational effects in a butterfly (Lohmus et al., 2018).

Evidence for microplastic effects specifically on butterfly populations is much more limited. Studies on Drosophila and broader terrestrial systems indicate plausible mechanisms, but these should not be presented as direct evidence of population-level effects in butterflies (Kwak et al., 2021; Jin et al., 2021; Zhang et al., 2021). A critical review should clearly distinguish demonstrated butterfly responses from hypotheses inferred from other organisms. This distinction strengthens rather than weakens the case for future research.

8. Species Traits and Differential Vulnerability

Butterfly species do not respond uniformly to climate change. Vulnerability emerges from interactions among dispersal capacity, habitat specialisation, host-plant specificity, voltinism, geographic range, thermal tolerance and phenological plasticity. Mobile species may track suitable conditions more rapidly, but dispersal is useful only where landscapes remain connected. Generalist species may substitute resources when one host or nectar plant declines, whereas specialists may be constrained by narrow resource requirements. However, neither generalism nor specialisation is a universal predictor; outcomes depend on landscape and climatic context. In the

Western Ghats, these trait categories correspond to differences among the five butterfly families and between widespread and endemic species (Section 12.3, Table 3).

Voltinism illustrates this complexity. Multivoltine species may benefit from longer warm seasons, but additional generations can also increase exposure to drought or resource depletion. Likewise, phenological plasticity can buffer moderate change but may fail when climatic conditions change faster than the species can adjust. Restricted-range and endemic species may be especially vulnerable because they have fewer opportunities to relocate as suitable climate space shifts.

9. Range Shifts and Elevational Redistribution

Poleward and elevational redistribution is among the best documented large-scale responses of butterflies. Parmesan et al. (1999) reported poleward movements of non-migratory European butterflies associated with warming, and Chen et al. (2011) demonstrated rapid climate-associated range shifts across taxa. Yet expansion at a leading edge does not necessarily compensate for contraction at a trailing edge. Dispersal barriers, habitat availability and host plants determine whether climatic suitability becomes actual occupancy, as demonstrated by studies of the silver-spotted skipper *Hesperia comma*, Hesperiidae, in Britain (Hill et al., 1999; Thomas et al., 2001).

Mountain systems provide a particularly clear test of climate tracking. In the Austrian Alps (Salzburg), Rödder et al. (2021) analysed six decades of records of mountain butterflies and found that mobile and generalist species tended to move uphill more than specialist and sedentary species. Habel et al. (2023), using records of lowland butterflies and burnet moths from the same region over seven decades, reported upslope shifts of more than 300 m in average occurrence and again found the strongest shifts in habitat-generalist and mobile species. In central Spain (Sierra de Guadarrama), butterfly communities shifted uphill by about 293 m between 1967–1973 and 2004–2005, with losses concentrated at low elevations among species restricted to the mountains (Wilson et al., 2007). These studies support an important synthesis: climate exposure determines the direction of potential movement, but species traits and landscape structure determine whether movement is possible.

High-elevation specialists face a “range compression” problem because suitable climate space may decrease with altitude. Conservation should therefore maintain habitat connectivity across elevational gradients rather than protecting only current occurrence sites. Whether range compression occurs among Western Ghats montane butterflies remains untested. Ecological niche modelling of endemic Western Ghats birds identified mid-elevation wet evergreen forests as potential climate refugia (Manna et al., 2024). Although this study was not focused on butterflies, its findings provide a basis for hypothesizing that similar

habitats may also serve as potential climate refugia for butterfly species, a possibility that requires further investigation.

10. Community Restructuring

Climate-driven changes in individual species accumulate to produce community restructuring. Warm-associated species may increase or colonise new areas while cold-associated species decline. Communities may consequently develop novel species combinations, altering competition, pollination and trophic interactions. Local species richness can even increase temporarily when colonisation exceeds extinction, while regional diversity declines through species loss. Species turnover and beta diversity are therefore often more informative than richness alone.

Geographic context determines community outcomes. In California, a 35-year dataset covering 159 butterfly species showed declining diversity at low-elevation sites, slower declines in the mountains and increased diversity at the highest (treeline) sites as lower-elevation species moved upslope (Forister et al., 2010). In central Spain, richness declined between surveys, particularly at low elevations (Wilson et al., 2007). Such contrasting patterns show that a single global trend cannot adequately describe community response. Community analyses should incorporate elevation, land use, habitat connectivity and species traits.

11. Integrative Synthesis: Climate Winners and Losers

Table 2. *Trait-based Synthesis of Potential Advantages and Vulnerabilities under Climate Change.*

Trait/context	Potential advantage	Potential vulnerability	Interpretation
High dispersal	Tracks suitable climates	Requires connected habitat	Movement capacity matters only when landscapes permit movement
Generalist resources	Can substitute hosts/ nectar sources	Still vulnerable to severe habitat loss	Generalism is a buffer, not immunity
Multivoltinism	May exploit longer warm seasons	More generations may face drought/resource stress	Flexibility can help under moderate warming
Restricted elevation	Few opportunities for movement	Habitat compression	High priority for mountain conservation
Phenological plasticity	Can adjust seasonal timing	Plasticity has limits	May delay vulnerability but not eliminate it

Host-plant specialisation	Efficient use of stable resources	Host loss or mismatch	Host-plant conservation is essential
Habitat connectivity	Facilitates movement and gene flow	Fragmentation blocks tracking	Landscape structure can determine persistence

Note: This table is derived mainly from the temperate studies discussed in Sections 4–10; its transfer to the Western Ghats is discussed in Section 12.4.

12. Tropical Systems and the Western Ghats

Much of the evidence for climate-driven butterfly change comes from temperate regions with long-running monitoring programmes. Tropical regions are comparatively underrepresented despite their high biodiversity. This geographic imbalance creates uncertainty about whether apparent differences between temperate and tropical responses reflect genuine biology or simply differences in data availability.

The Western Ghats provide an important tropical mountain system because steep elevation gradients, high endemism and strong seasonality create complex climatic and ecological conditions. Naik et al. (2022) recorded 43,118 individuals of 175 species across eight landscapes in the coastal plains and foothills of Dakshina Kannada, Karnataka, demonstrating substantial diversity and strong differences among habitats. However, inventories and short-term surveys cannot by themselves establish climate-driven trends. Attribution requires repeated standardised sampling linked to temperature, rainfall, habitat and land-use data.

12.1 Diversity, Endemism and Taxonomic Composition

A literature-based analysis recorded 334 butterfly species from the Western Ghats, with the southern Western Ghats richer in species and genera than the northern part, endemic species concentrated between about 10°N and 12°N, and evergreen forest supporting the greatest number of endemics (Padhye et al., 2012). Kunte (2008) assessed the region's butterflies by family and by categories of endemism (endemic to the Western Ghats, shared with Sri Lanka, or restricted to peninsular India). At Eravikulam National Park, a montane site in Kerala, 198 butterfly species were recorded, 22 of them strictly endemic to the Western Ghats (Sadasivan et al., 2022). Larval host-plant records are available for about 320 Western Ghats butterfly species (Nitin et al., 2018). These sources establish which taxa occur where, but none of them tests for climate-driven change.

12.2 Documented Climate-Sensitive Processes

The best-documented climate-linked process in Western Ghats butterflies is the monsoon-driven migration of milkweed butterflies (Danainae, Nymphalidae). Each year, species including *Tirumala septentrionis*, *T. limniace*, *Euploea sylvester* and *E. core* migrate between the Western Ghats and the southern Eastern Ghats and eastern plains. Kunte (2005) observed movement across the plains of southern India towards the Western Ghats in October–November and towards the plains in April–May, and proposed that the migratory habit evolved to avoid the torrential south-west monsoon in the larval habitats of Western Ghats evergreen and semi-evergreen forests. Females enter a non-reproductive state during migration and breed after arrival (Bhaumik & Kunte, 2017). Because this migration is tied to the monsoon rather than to temperature, it offers a clear mechanistic route through which changes in monsoon timing or intensity could alter breeding, movement and population dynamics. This is a hypothesis: no study identified in this review has tested whether the timing of migration has changed.

Seasonal structure has also been documented in surveys. In the southern plains at Kalpakkam, Tamil Nadu, species richness and abundance were highest during the north-east monsoon and winter, with Nymphalidae being the dominant family (Hussain et al., 2011); earlier work in the northern Western Ghats described seasonal patterns of abundance and diversity in four habitats (Kunte, 1997). Such baselines are valuable but are not trend data.

12.3 Taxon-Level Synthesis by Family

Table 3 maps the five major families onto Western Ghats taxa documented in the literature reviewed, the traits that may influence climate sensitivity and the status of the evidence. The trait entries are hypotheses derived from the mechanisms in Sections 4–10 and are not demonstrated responses.

Table 3. *Western Ghats Butterfly Families: Example Taxa, Hypothesised Climate-Relevant Traits and Evidence Status.*

Family	Western Ghats taxa cited (endemic status)	Hypothesised climate-relevant traits	Evidence status
Papilionidae	*Pachliopta pandiyana*, *Papilio dravidarum*, *Troides minos* (endemic to the Western Ghats); *Papilio polymnestor* (peninsular India and Sri Lanka) (Kunte, 2008)	Large, mobile species whose larvae use particular host-plant groups (Nitin et al., 2018); host-plant distribution and phenology may limit responses	Western Ghats: checklists and host-plant records only; no climate-trend data identified

Pieridae	*Appias wardii* (endemic); *Pareronia ceylanica* (Western Ghats and Sri Lanka); *Prioneris sita* (peninsular India and Sri Lanka) (Kunte, 2008)	Many species are mobile; Pieridae and Nymphalidae include the best-evidenced migratory butterflies (Chowdhury et al., 2021a); mobility may aid tracking only where habitat is connected	Western Ghats: checklists and seasonal surveys; global niche models exist for migratory species (Chowdhury et al., 2021b)
Nymphalidae	Danainae: *Tirumala septentrionis*, *Euploea sylvester*. Endemic: *Kallima horsfieldi*, *Idea malabarica*. Western Ghats and Sri Lanka: *Cirrochroa thais*, *Mycalesis patnia* (Kunte, 2008)	Monsoon-linked bidirectional migration in danaines; forest-interior species may depend on canopy microclimate (Suggitt et al., 2011)	Strongest Western Ghats mechanistic evidence (Kunte, 2005; Bhaumik & Kunte, 2017); temperate analogues include *Speyeria mormonia* (Boggs & Inouye, 2012) and *Melitaea cinxia* (Hanski & Saccheri, 2006)
Lycaenidae	*Cigaritis conjucta*, recently described from mid-elevation evergreen forest in Kodagu, Karnataka (Kunte et al., 2024)	Narrow habitat association and a minimal baseline; potential vulnerability to loss of mid-elevation evergreen forest	No Western Ghats climate data; temperate analogue *Aricia agestis* (Pateman et al., 2012)
Hesperiidae	*Caltoris canaraica*, *Thoressa honorei* (endemic to the Western Ghats) (Kunte, 2008)	Range-restricted endemics whose thermal limits and host requirements are largely undocumented	Checklists only; temperate analogue *Hesperia comma*, whose range margin depends on climate and habitat (Hill et al., 1999)

No family has long-term, taxon-resolved climate-trend data from the Western Ghats in the literature reviewed. Species lists are illustrative, not exhaustive.

12.4 Transferability of Temperate Evidence

Most quantitative evidence in Sections 4–10 comes from temperate Europe and North America (Tier 3), and its transfer to the Western Ghats should be treated cautiously for four reasons. First, seasonality in peninsular India is organised around the monsoon: southern Indian danaine migration is thought to be driven by the south-west monsoon rather than by temperature (Kunte, 2005), and seasonal richness in the southern plains peaks in the north-east monsoon and winter (Hussain et al., 2011), whereas the temperate phenological literature is built around temperature-driven spring advancement. Second, the Western Ghats combine a long latitudinal axis with elevations reaching about 2,700 m and a concentration of endemic species in southern evergreen forests (Kunte, 2008; Padhye et al., 2012), so the range-compression mechanism described in

Section 9 may be important but has not been tested for butterflies. Third, baseline monitoring is sparse, so climate effects cannot yet be separated from land-use change in a region described as anthropogenically active and ecologically sensitive (Naik et al., 2022). Fourth, evidence from other Western Ghats taxa is only indirectly informative: niche models for endemic birds identify mid-elevation wet evergreen forest as potential refugia (Manna et al., 2024), which suggests, but does not show, that similar zones may matter for butterflies. The findings of Sections 4–10 are therefore best read as hypotheses for the Western Ghats rather than as established responses.

12.5 Priorities for Western Ghats Monitoring

Future Western Ghats studies should combine fixed transects with climatic measurements, host-plant phenology, elevation, vegetation structure and landscape connectivity. Particular attention should be given to endemic and high-elevation species, for which climate tracking may be constrained by habitat compression. Monsoon timing and short-duration climatic extremes should also be incorporated because tropical responses may not follow temperate patterns. Priority taxa include range-restricted endemics in each family (Table 3), migratory danaine Nymphalidae and forest-interior species of mid-elevation evergreen forest.

13. Evolutionary Responses and Limits of Adaptation

Butterfly populations can respond through phenotypic plasticity, behavioural adjustment, dispersal and evolutionary change. Changes in voltinism, diapause timing, thermal tolerance or host use may improve synchrony with new climatic conditions. However, evolutionary responses require heritable variation and sufficient demographic opportunity. Small, isolated or highly specialised populations may have limited capacity to respond rapidly.

Landscape connectivity also affects evolutionary potential. Fragmentation can reduce gene flow and population size, while expanding populations may experience increased gene flow during range shifts. Metapopulation and landscape-genetic processes are therefore relevant to climate adaptation (Hanski & Saccheri, 2006; Van Dyck et al., 2003). Conservation should protect not only current population abundance but also connectivity and genetic variation.

14. Conservation Implications

Climate-smart conservation should anticipate movement rather than protect only present-day distributions. Habitat corridors and stepping-stone habitats can facilitate natural redistribution, while elevational connectivity may be especially important in mountains. Microclimatic refugia can be maintained through canopy cover, vegetation complexity and habitat heterogeneity. Host-

plant conservation must accompany protection of adult nectar resources because larval survival depends on suitable plants.

Assisted migration may be considered for selected species with extremely limited dispersal and rapidly disappearing climatic space, but it carries ecological and genetic risks and should not replace habitat protection. Citizen science can increase geographic coverage, but observation effort and detection bias must be considered. Standardised monitoring remains essential for robust trend detection (Van Swaay et al., 2008).

15. Knowledge Gaps and Future Research

- Long-term standardised monitoring of tropical butterfly communities, especially across elevation gradients in the Western Ghats.
- Experimental estimates of thermal limits for endemic and habitat-specialist species.
- Integrated analyses of temperature, precipitation, extreme events and microclimate.
- Paired monitoring of butterfly and host-plant phenology to quantify demographic effects of mismatch.
- Assessment of climate change together with habitat fragmentation, pesticides and other environmental stressors.
- Population-genetic and genomic studies distinguishing plasticity from local adaptation.
- Species-distribution and community models incorporating dispersal limitation, host plants, land use and biotic interactions.
- Direct experimental testing of emerging-contaminant exposure in butterflies rather than relying on extrapolation from other insects.
- Long-term monitoring of extreme climatic events and their demographic consequences.
- Climate-smart conservation planning that protects current populations while maintaining routes for future range movement.

16. Conclusions

Climate change is reshaping butterfly populations and communities through interconnected physiological, phenological, demographic and geographic processes. Earlier seasonal activity, distributional shifts and changes in community composition are recurring patterns, but their magnitude and direction vary among species and regions. The central conclusion is therefore not that warming uniformly benefits or harms butterflies, but that outcomes depend on interactions among climate exposure, species traits, resource availability and landscape connectivity.

Mobile, generalist and phenologically flexible species may have greater capacity to track changing conditions, whereas specialists, sedentary species and restricted-range endemics can

face stronger constraints. Even apparently favourable responses such as earlier emergence or range expansion can become detrimental when accompanied by host-plant mismatch, habitat fragmentation or extreme climatic events. Climate change should consequently be evaluated within a multi-stressor framework.

For tropical biodiversity hotspots such as the Western Ghats, the major limitation is the scarcity of long-term standardised baseline data. Establishing monitoring across elevation and habitat gradients is essential for determining which changes are genuinely climate driven. Conservation should combine habitat connectivity, host-plant management, microclimate refugia and climate-informed reserve design. Future research should move from documenting isolated observations toward mechanistic, comparative and predictive approaches that integrate climate, species traits, ecological interactions and landscape structure. The evidence base for Western Ghats butterflies currently consists largely of inventories, short-term seasonal surveys and studies of monsoon-linked migration in danaine Nymphalidae; conclusions drawn from temperate Europe and North America should therefore be treated as hypotheses for the region until long-term, taxon-resolved data are available.

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