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Climate Change and Neotropical Mangrove Insects: A Critical Review of Ecological Pathways, Evidence, and Knowledge Gaps

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Abstract
Mangrove ecosystems of the Neotropics occur across the Caribbean, Central America, northern South America, Brazil, and southern Florida and support diverse insect assemblages that contribute to pollination, herbivory, decomposition, predation, parasitism, and nutrient cycling. Climate change represents an increasingly important driver of change in these systems because it alters both the physical environment occupied by insects and the biological interactions on which many insect populations depend. This review synthesizes literature on the potential and documented impacts of increasing temperature, altered precipitation, drought, sea-level rise, salinity change, tidal modification, hurricanes, and other extreme climatic events on insects associated with neotropical mangrove ecosystems. Particular attention is given to insect-mediated pollination because evidence from *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa* demonstrates that insect activity, flowering phenology, mating systems, and mangrove reproductive success are closely interconnected. The available literature indicates that climate change may affect mangrove insects through direct physiological mechanisms, including altered metabolism, development, survival, and reproduction, and indirectly through changes in mangrove distribution, habitat structure, floral resources, hydrology, salinity, and species interactions. A major concern is phenological mismatch, whereby climatic changes alter the timing of insect emergence or activity differently from mangrove flowering. Extreme disturbances may also restructure insect communities rapidly; hurricane-associated reductions in pollinator richness and diversity in Florida mangroves provide an important analogue for understanding the ecological consequences of increasingly intense climatic disturbances. However, direct climate-change studies focused specifically on neotropical mangrove insects remain scarce. Existing knowledge is concentrated on a limited number of mangrove species and locations, while many taxa, particularly small Diptera, solitary Hymenoptera, herbivores, detritivores, parasitoids, and immature insects, remain poorly documented. The review concludes that climate impacts on mangrove insects should be understood as interacting pathways linking climatic exposure, insect physiology, mangrove phenology, habitat transformation, and ecological networks. Long-term, species-level, climate-linked monitoring is urgently needed, particularly in under-studied neotropical regions such as the Caribbean and northern South America.

Keyword: Climate change, Mangrove ecosystems, Neotropics, Insect diversity, Insect pollinators, Phenology, Sea-level rise. Extreme weather

1. Introduction

Mangrove ecosystems under climate change

Mangrove forests occupy tropical and subtropical intertidal environments and form an ecotonal interface between terrestrial, freshwater, and marine systems [2, 3, 5, 6, 7, 17]. The structural complexity created by trunks, canopies, roots, sediment surfaces, litter, flowers, and tidal creeks supports diverse assemblages of organisms. Insects constitute an important component of mangrove biodiversity [2, 3, 5, 6, 7, 17].

Mangroves provide habitat for insects with different ecological strategies. These include phytophagous species associated with leaves, flowers, bark, propagules, and wood; pollinators visiting nectar and pollen resources; predators inhabiting foliage and sediment-associated habitats; decomposers exploiting litter and dead wood; parasitoids; scavengers; and species whose larval stages depend on productive aquatic or semi-aquatic habitats. Recent biodiversity research has demonstrated that mangroves should not be regarded as insect-poor habitats merely because they possess relatively low plant diversity. Yeo *et al.* (2021) [27] found that mangroves supported a remarkably species-rich and distinct insect fauna, emphasizing the ecological importance of conserving these coastal habitats.

Climate change is now an additional driver acting upon mangrove ecosystems already exposed to pressures from coastal development, pollution, fragmentation, resource extraction, altered hydrology, and habitat conversion and is also recognized as a major driver of biodiversity change in coastal ecosystems. Sea-level rise, global warming, climatic extremes, storm surges, and interacting non-climatic stressors may alter the distribution and persistence of coastal habitats. Saintilan *et al.* (2023) [22] reported that increasing rates of relative sea-level rise may exceed the capacity of some mangrove systems to maintain their elevation relative to rising water levels.

The consequences for insects in mangrove ecosystems may therefore be substantial. Unlike many terrestrial forests, mangroves occur within a narrow elevation range governed by tidal inundation and salinity. Consequently, relatively small alterations in temperature, rainfall, sea level, sediment supply, and freshwater discharge can change vegetation composition and habitat structure. Insects dependent upon particular mangrove species, flowering periods, microhabitats, or trophic resources may consequently experience indirect climate effects even where climatic conditions do not immediately exceed their physiological tolerances.

The Neotropics are of particular importance because they contain extensive mangrove systems distributed across the Caribbean, Central America, northern South America, the Atlantic coast of South America, and the Pacific coast from Mexico to South America [7, 17]. Dominant and ecologically important mangrove taxa include *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*, and, in some regions, the mangrove associate, *Conocarpus erectus* [7, 17]. These ecosystems support distinctive insect communities and important plant–insect interactions, yet the literature directly examining climate change impacts on Neotropical mangrove insects remains fragmented.

Climate sensitivity of tropical and Neotropical insects

Insects are ectotherms, and their development, metabolism, activity, reproduction, and survival are strongly influenced by environmental temperature. Deutsch *et al.* (2008) [9] argued that tropical ectotherms may be especially vulnerable to warming because many already occupy relatively warm environments and may have narrower thermal safety margins. More recently, Holzmann *et al.* (2026) [14], using field-derived thermal tolerance data from approximately 2,300 insect species across Afrotropical and Neotropical gradients, reported limited thermal buffering among many lowland tropical insects. Their results are particularly significant for this review because they included Neotropical communities and indicated that tropical lowland insects may possess limited capacity to compensate physiologically for future warming.

Temperature, however, does not operate independently. Climate change modifies the frequency and duration of heat extremes, precipitation regimes, humidity, drought, flooding, storm disturbance, and seasonal predictability. Robinet & Roques (2010) [21] and Harvey *et al.* (2023) [12] emphasized that insect responses to climate change are often nonlinear and taxon-specific. Some species may initially benefit from warmer temperatures through accelerated development or extended periods of activity, whereas others may experience physiological stress, increased mortality, reduced body size, disrupted reproduction, or mismatches with host plants and natural enemies.

For insects in mangroves, climate exposure is especially complex because terrestrial atmospheric conditions interact with marine and estuarine processes. A mangrove insect may simultaneously experience:

- Increasing air temperature;
- Elevated canopy or surface temperatures;
- Changes in humidity;
- Altered rainfall and freshwater input;
- Changes in pore-water and sediment salinity;
- Increased tidal inundation;
- Storm damage to vegetation;
- Shifts in flowering and fruiting;
- Changes in litter production and decomposition; and
- Reorganization of the wider mangrove community.

Therefore, climate vulnerability cannot be evaluated solely from regional temperature projections. It must also incorporate habitat-mediated changes.

Climate change introduces an additional level of ecological complexity because insects and mangroves may not respond to changing environmental conditions at the same rate or through the same mechanisms. Rising temperatures can directly affect insect metabolism and development while also modifying mangrove flowering. Altered rainfall can change humidity, freshwater input, salinity, and the availability of aquatic breeding habitats. Sea-level rise may alter mangrove zonation and inundation regimes, while storms can rapidly remove vegetation, destroy flowers, modify insect habitat, and restructure pollinator communities. Thus, the effect of climate change on insects in mangrove ecosystem is not restricted to a single environmental variable but involves interacting physiological, ecological, and landscape-level pathways.

A major theoretical foundation for the present review is provided by Bhagarathi & Maharaj (2023) [4] in their critical review that examined the impact of climate change on insect biology, ecology, population dynamics, and pest management. Their study systematically reviewed literature spanning more than a century and demonstrated that climate change can affect insect development, survival, reproduction, behaviour, phenology, geographical distribution, population abundance, species interactions, and ecological relationships. Their review established several mechanisms directly relevant to this study: (1) Temperature can alter insect metabolism and developmental rates. (2) Changes in climatic conditions can influence survival and reproductive success. (3) Climate variability can alter insect population growth and seasonal abundance. (4) Species may shift their geographical distributions in response to changing climatic conditions. (5) Climate change can disrupt relationships among insects, plants, hosts, prey, predators, and other organisms. (6)

Responses vary among species because insects differ in physiology, life history, habitat requirements, and adaptive capacity. These conclusions provide an essential conceptual bridge between general insect climate biology and the specialized environmental conditions of mangrove ecosystems. In mangroves, the processes described by Bhagarathi & Maharaj (2023) [4] are likely to interact with sea-level rise, salinity, tidal inundation, and climate-induced changes in mangrove vegetation.

Although the Neotropics contain some of the world's most biologically diverse terrestrial and coastal ecosystems, yet insect diversity remains somewhat incompletely documented in many countries, and this limitation is particularly pronounced for specialized coastal habitats. The lack of baseline information creates a major challenge for climate-change research: population change cannot be quantified reliably when original species composition, abundance, seasonal dynamics, and ecological interactions remain poorly characterized.

This problem is especially relevant to the Guiana Shield and Guyana. This study identified a strong geographical bias in mangrove insect research and emphasized the need for more species-level and long-term studies. Similar limitations apply to climate-focused investigations. Consequently, the apparent scarcity of climate-change effects in some Neotropical mangrove regions should not be interpreted as evidence of ecological stability; in many cases, the necessary monitoring data do not yet exist.

Neotropical mangrove forests include communities dominated by species such as *Rhizophora mangle* L., *Rhizophora racemosa* G. Mey., *Avicennia germinans* (L.) L., *Avicennia schaueriana* Stapf & Leechm. ex Moldenke, *Laguncularia racemosa* (L.) C.F. Gaertn., *Conocarpus erectus* L., and, in more geographically restricted areas, *Pelliciera rhizophorae* [7, 17]. These mangroves occur across broad climatic gradients and experience different combinations of rainfall, temperature, hurricanes, freshwater discharge, sediment supply, and sea-level change. Such heterogeneity makes the Neotropics particularly suitable for investigating how climatic change affects insect communities.

The literature guiding the present article similarly identifies climatic variability, temperature, precipitation, tidal conditions, mangrove flowering phenology, and anthropogenic disturbance as major influences on mangrove insects and pollination. Further evidence from other studies by Memmott *et al.* (2007) [19], Landry (2013a) [17], Sánchez-Bayo & Wyckhuys (2019) [23], Bhagarathi & Maharaj (2023) [4], Bhagarathi & Da Silva (2024) [3], Bhagarathi *et al.* (2025a; 2025b) [5, 6] and Bhagarathi *et al.* (2026) [7] emphasize substantial knowledge gaps in the Caribbean and South America and recommend baseline inventories and long-term monitoring.

However, a critical distinction is required between direct evidence and ecological inference. There are relatively few studies that experimentally or longitudinally demonstrate that anthropogenic climate change has directly caused population changes in a particular neotropical mangrove insect species. Much of the available evidence instead consists of studies demonstrating: (a) climate sensitivity of insects generally; (b) climate sensitivity of mangrove ecosystems; (c) climate-related influences on mangrove flowering and reproductive biology; and (d) responses of mangrove insect communities to environmental disturbances such as hurricanes and habitat alteration. The most scientifically defensible synthesis therefore integrates these lines of evidence while clearly recognizing the limitations of the current literature.

The aim of this review is to synthesize and critically evaluate the available literature on the real and potential impacts of climate change on insect populations, communities, and ecological functions in Neotropical mangrove ecosystems.

2. Materials and Methods

Search Strategy

A structured thematic literature review was conducted to identify and synthesize published scientific literature relevant to the impact of climate change on insects associated with Neotropical mangrove ecosystems. The review focused primarily on recent literature while also incorporating older foundational studies where these were necessary to establish the ecological, reproductive, and pollination biology of important mangrove species.

The search strategy was developed around the intersection of three major themes: climate change and climatic variability, Neotropical mangrove ecosystems, and mangrove-associated insects and insect-mediated ecological processes. Because relatively few studies directly address all three themes simultaneously, the search was broadened to include studies examining tropical and Neotropical insects, mangrove responses to climate change, mangrove reproductive ecology, plant-pollinator interactions, insect phenology, and extreme climatic disturbances.

Literature searches were guided by thematic keywords and Boolean combinations designed to capture direct and indirect pathways through which climate change may influence mangrove insect communities. The principal search combinations included:

- "Climate change" AND "mangrove" AND "insects"
- "Neotropical mangrove" AND "pollinators"
- "*Rhizophora mangle*" AND "pollination"
- "*Avicennia germinans*" AND "insect visitation"
- "*Laguncularia racemosa*" AND "pollinators"
- "Mangrove" AND "phenology" AND "climate"
- "Mangrove" AND "hurricane" AND "pollinators"
- "Insect climate change" AND "phenological mismatch"
- "Sea-level rise" AND "mangrove habitat"
- "Temperature" AND "insect physiology" AND "tropics"

These search terms were used to identify studies addressing the direct effects of climatic variables on insects as well as indirect effects resulting from changes in mangrove habitat, hydrology, salinity, flowering phenology, food resources, and ecological interactions. Priority was given to peer-reviewed scientific studies addressing species-level interactions, climatic drivers, long-term ecological patterns, extreme climatic events, and Neotropical mangrove ecosystems. Foundational publications were also retained where they provided essential ecological information on mangrove reproduction and insect-mediated pollination.

The literature search was therefore intentionally broader than a simple search for studies containing the exact phrase "climate change and Neotropical mangrove insects." This approach was necessary because direct empirical studies specifically examining climate-change responses of insects within Neotropical mangroves remain scarce. Consequently, relevant studies were examined to determine whether they provided direct evidence, mechanistic evidence, or ecological context for understanding potential climate-related changes in mangrove insect communities. The literature identification and screening procedures were guided by relevant principles of transparent evidence identification and selection as shown in Figure 1. The final evidence base was synthesized using a structured thematic approach (Page *et al*., 2021)

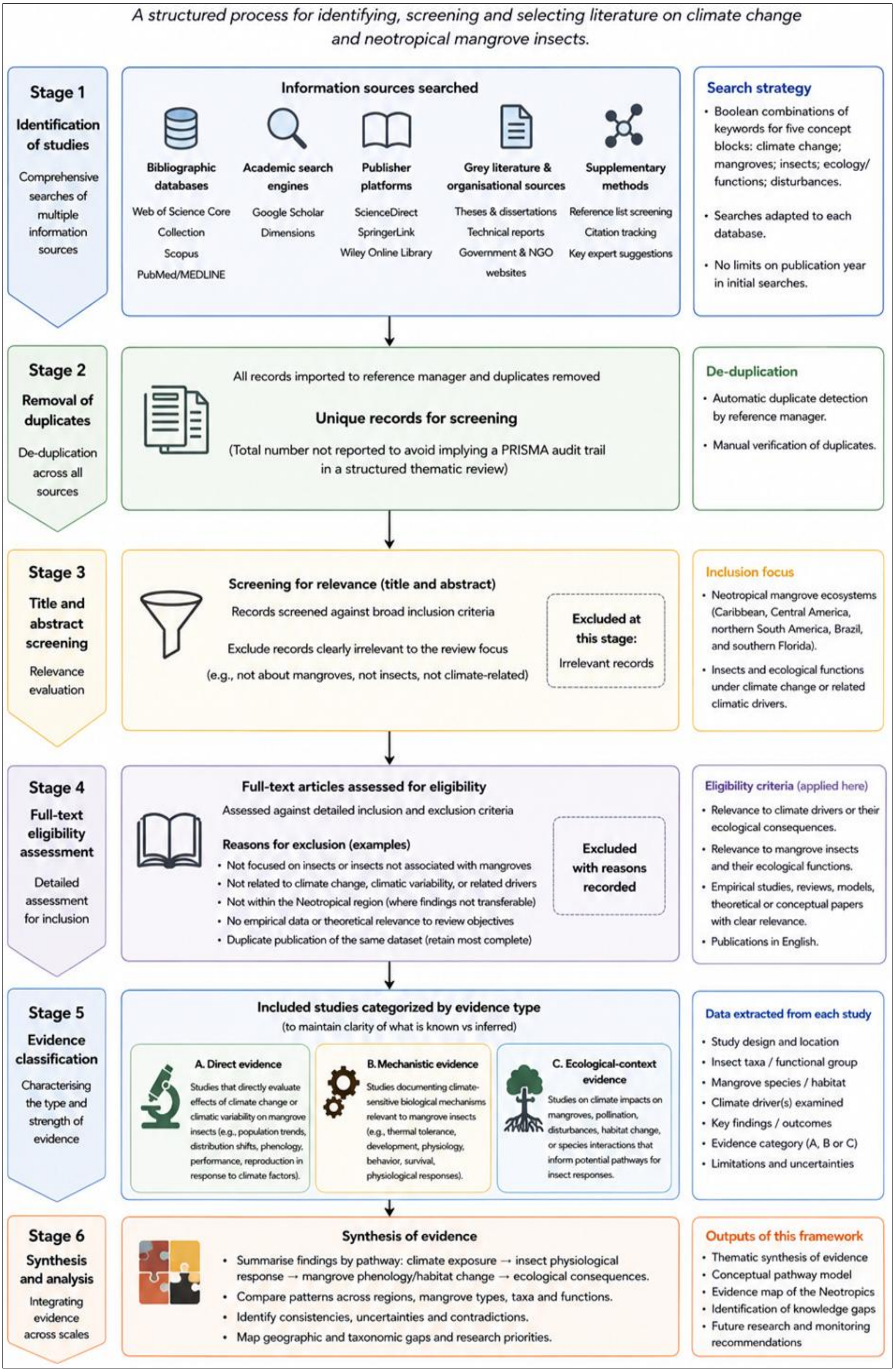

Fig 1: Literature search and study-selection framework for the review

Inclusion Criteria

This review aimed to synthesize and critically evaluate the available literature concerning the actual and potential impacts of climate change on insect populations, communities, diversity, ecological interactions, and ecosystem functions in Neotropical mangrove ecosystems. The selection of articles was based on the following inclusion criteria:

- Relevant and recent scientific literature: Priority was given to recent peer-reviewed literature addressing climate change, biodiversity, mangrove ecosystems, insect ecology, pollination, phenology, and environmental change.
- Foundational literature: Older publications were included where necessary to establish baseline knowledge on mangrove reproductive ecology, pollination biology, insect–plant interactions, and the ecological roles of mangrove-associated insects.
- Studies involving insects in mangrove ecosystems: Research documenting insect diversity, abundance, distribution, ecological functions, or species interactions within mangrove habitats was considered relevant.
- Studies on Neotropical mangrove plant–insect interactions: Particular attention was given to studies involving important Neotropical mangrove species, including *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa*, and their relationships with insect flower visitors and pollinators.
- Studies addressing climatic effects on insects: Articles examining the effects of temperature, rainfall, humidity, drought, extreme heat, or other climatic variables on insect physiology, survival, development, reproduction, distribution, abundance, behaviour, or phenology were included where they provided relevant mechanistic information.
- Studies addressing climatic effects on mangrove ecosystems: Research examining sea-level rise, salinity change, tidal inundation, habitat transformation, vegetation shifts, altered hydrology, and storm effects on mangrove ecosystems was included because these environmental changes may indirectly influence insect populations.
- Studies examining phenological relationships: Research addressing changes in flowering phenology, insect emergence, seasonal activity, pollinator visitation, and plant–pollinator synchrony was included because temporal mismatches represent an important potential pathway through which climate change may affect mangrove ecological interactions.
- Studies involving hurricanes and extreme weather events: Research documenting the effects of hurricanes, severe storms, or other extreme climatic disturbances on mangrove vegetation, insect communities, pollinator assemblages, or plant reproductive systems was considered relevant.
- Studies addressing climate, habitat change, and biodiversity: Publications examining interactions among climatic change, habitat transformation, fragmentation, species interactions, and insect biodiversity were included where they contributed to the conceptual understanding of climate vulnerability.
- English-language scientific publications: Literature available in English and containing sufficient scientific information to address the objectives of the review was considered for inclusion.

These criteria are consistent with the review's established inclusion framework, which covers mangrove insects, Neotropical plant-pollinator interactions, insect physiology and phenology, mangrove flowering and reproduction, sea-level rise, salinity, inundation, storms, and interactions between climate, habitat change, and biodiversity.

Classification of Included Literature

An important methodological consideration in this review was that not every selected publication was required to demonstrate a direct, experimentally established effect of anthropogenic climate change on a particular insect species in a Neotropical mangrove. Given the limited availability of such studies, the literature was classified according to its contribution to understanding climate-related impacts:

1. **Direct evidence** - studies directly documenting climatic or extreme-weather effects on mangrove insects or insect-mediated ecological processes.
2. **Mechanistic evidence** - studies demonstrating biological mechanisms through which climatic variables may affect insect physiology, development, survival, reproduction, phenology, or ecological interactions.
3. **Ecological-context evidence** - studies documenting mangrove insect diversity, pollination biology, habitat responses, plant phenology, sea-level rise, salinity, or ecosystem changes that provide ecological context for evaluating potential climate impacts.

This classification was particularly important because it prevented indirect evidence from being presented as though it were direct proof of climate-change impacts. The review therefore explicitly distinguishes between documented climatic or disturbance responses and biologically plausible or mechanistically supported climate-change pathways.

3. Results

Literature relevant to the review was identified using the thematic search framework described above. Searches produced literature covering a wide range of subjects, including climate change and mangrove ecosystems, insect physiological responses to temperature, insect phenology, mangrove flowering, plant-pollinator interactions, sea-level rise, salinity, tidal inundation, hurricanes, extreme weather, habitat transformation, and insect biodiversity.

However, the search also revealed an important limitation in the available scientific literature: studies directly investigating climate change and insects specifically within Neotropical mangrove ecosystems remain relatively limited. In contrast, substantially more literature is available on mangrove responses to climate change, general climate effects on insects, and climate-sensitive plant-pollinator interactions. This uneven distribution of evidence represents an important finding of the review and justified the inclusion of mechanistic and ecological-context literature alongside directly relevant mangrove studies.

The literature identified through the search was subsequently organized into five principal evidence categories:

1. Direct climatic exposure of insects, particularly the effects of temperature and humidity on insect physiology and ecological performance.
2. Climate-mediated transformation of mangrove habitats, including sea-level rise, salinity changes, increased or altered inundation, and changes in mangrove vegetation and habitat structure.
3. Changes in temporal synchrony, particularly potential changes in the relationship between insect activity,

emergence, or visitation and the timing of mangrove flowering.
4. Extreme-event effects, particularly the ecological consequences of hurricanes and severe storms on insect communities, pollinator assemblages, floral resources, and mangrove reproductive processes.
5. Indirect ecological and community effects, including changes in resource availability, competition, predation, parasitism, pollination networks, and other insect-mediated ecological interactions.

The search results demonstrated that the strongest species-level evidence relevant to Neotropical mangrove insects is concentrated primarily within the area of plant–pollinator ecology. In particular, published studies have provided important information on the pollination biology of *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa*. Sánchez-Núñez & Mancera-Pineda (2012) [24], for example, documented 25 insect flower-visitor species representing three insect orders and 12 families in a study of these major mangrove species in the southwestern Caribbean. This evidence demonstrates that insect assemblages differ in their effectiveness and that pollinator specialization and functional redundancy may influence mangrove reproductive outcomes.

Similarly, the search identified evidence showing that insect-mediated interactions can be altered by changes in environmental conditions. Research summarized in the review showed that co-flowering *A. germinans* and *L. racemosa* may compete for insect pollination services and that bees, wasps, flies, and butterflies can contribute to their floral visitor communities, with *Apis mellifera* reported as the most common floral visitor in the referenced Florida study. Such evidence is important in the climate-change context because warming and changes in precipitation may potentially alter flowering periods and insect activity independently, thereby creating changes in temporal overlap between plants and their pollinators.

Overall, the results of the literature search indicate that evidence concerning climate change and Neotropical mangrove insects is fragmented rather than completely absent. Relevant information is distributed across several research fields, including insect climate biology, mangrove ecology, coastal climate change, plant–pollinator interactions, reproductive ecology, and extreme-event ecology. Consequently, an integrated thematic synthesis was required to identify the pathways through which climate change may affect mangrove insect communities.

The principal pathways identified from the literature are summarized as follows:

- Rising temperature may alter insect metabolism, development, movement, feeding, reproduction, survival, emergence, and distribution.
- Changes in rainfall and humidity may influence insect activity and seasonal population patterns while simultaneously affecting freshwater input and mangrove environmental conditions.
- Sea-level rise and altered inundation may transform the structure and spatial distribution of mangrove habitats and associated insect microhabitats.
- Changes in salinity and hydrology may influence immature insect stages, host plants, floral resources, litter environments, and habitat suitability.
- Climate-induced changes in mangrove phenology may alter the synchrony between insect activity and flowering.
- Hurricanes and severe storms may rapidly reduce or restructure insect and pollinator communities while simultaneously changing canopy structure, flowers, and resource availability.
- Indirect ecological effects may occur through changes in competition, herbivory, predation, parasitism, decomposition, and plant–pollinator networks.

The review therefore supports the conclusion that climate change should not be examined as a single environmental factor acting directly on insects. Instead, Neotropical mangrove insects should be viewed as components of an interconnected ecological system in which climatic changes can simultaneously affect insect physiology, mangrove habitat structure, hydrology, salinity, floral resources, phenology, and species interactions. This conceptual approach is consistent with the broader synthesis of the review, which emphasizes interacting direct and indirect pathways rather than a simple one-directional climate-insect relationship.

4. Discussion

General Pattern of Evidence

The literature reveals an important asymmetry in knowledge. Mangrove responses to climate change are relatively well developed, and there is extensive general literature on climate impacts on insects and plant–pollinator interactions. In contrast, studies directly examining climate change and insects specifically within Neotropical mangrove forests remain limited.

The evidence can therefore be organized into five major categories:

1. Direct climatic exposure of insects, particularly temperature and humidity.
2. Climate-mediated transformation of mangrove habitat, including sea-level rise, salinity, inundation, and vegetation shifts.
3. Changes in temporal synchrony, particularly between insect activity and mangrove flowering.
4. Extreme-event effects, especially hurricanes and severe storms.
5. Indirect community effects, including altered competition, predation, parasitism, resource availability, and pollination networks.

Landry (2013a,b) [17, 18] showed that co-flowering *A. germinans* and *L. racemosa* can compete for insect pollination services in Florida. Bees, wasps, flies, and butterflies visited both species, with *Apis mellifera* being the most common floral visitor. The results demonstrate that changes in flowering overlap may alter insect visitation and, consequently, plant mating patterns.

These studies are particularly important in a climate-change context because climate warming and altered precipitation may shift flowering phenology and insect activity independently.

Climate Change and Pollination in Neotropical Mangroves

Evidence from the Southwestern Caribbean

Sánchez-Núñez & Mancera-Pineda (2012) [24] provide one of the most important direct sources for understanding insect-mediated reproduction in Neotropical mangroves. They investigated pollination effectiveness and fruit set in *Rhizophora mangle*, *Laguncularia racemosa*, and *Avicennia germinans* in the Southwestern Caribbean.

The study by Sánchez-Núñez & Mancera-Pineda (2012) [24] recorded 83 flower visitors representing three insect orders, 12 families, and 25 species. Importantly, not all floral visitors were equally effective pollinators. This distinction is critical when assessing climate risk because changes in total insect abundance may not accurately predict changes in pollination services.

Table 1: Pollination characteristics of major Neotropical mangroves reported by Sánchez-Núñez & Mancera-Pineda (2012) [24]

Mangrove species and common name	Family	Pollination characteristic	Representative effective insect evidence	Reported fruit set	Climate-change relevance
Rhizophora mangle (Red mangrove)	Rhizophoraceae	Ambophilous; insect pollination more important than traditionally assumed	*Copestylum* sp. 1 (Diptera: Syrphidae) identified as a highly effective pollinator	7.2%	Warming or phenological change could affect hoverfly activity and pollen transfer
Laguncularia racemosa (White mangrove)	Combretaceae	Most specialized pollination system among the three species	Three highly effective insect pollinators reported	7.9%	Specialized systems may be more vulnerable if key pollinator activity shifts
Avicennia germinans (Black mangrove)	Acanthaceae	Least specialized of the three systems; multiple effective pollinators	Four highly effective insect pollinators reported	29%	Greater pollinator redundancy may potentially buffer some disruption

The results demonstrate that climate risk may differ among mangrove species according to the degree of pollinator specialization. A plant dependent upon a relatively small number of effective pollinators may be vulnerable if climatic conditions reduce the abundance or activity of those taxa. In contrast, a plant with multiple effective pollinators may possess greater functional redundancy. Table 1 examine pollination characteristics of major Neotropical mangrove species.

However, redundancy should not be assumed to guarantee resilience. Climate change can affect multiple species simultaneously. Furthermore, species that remain present may differ substantially in pollination efficiency.

Climate Change Pathways Affecting Neotropical Mangrove Insects

Rising Temperature

Temperature is one of the most important climatic determinants of insect performance because insects are ectothermic. Their metabolic rate, development, movement, feeding, reproduction, and survival are strongly influenced by environmental temperature. Moderate warming may accelerate development and potentially increase the number of generations completed annually by some species. However, these benefits are not unlimited. Once temperatures approach or exceed physiological optima, survival, fecundity, immune performance, and reproductive success may decline.

This relationship is especially relevant in tropical environments. Many tropical insects experience relatively narrow seasonal temperature ranges and may consequently have limited physiological buffering against sustained warming or extreme heat. A mangrove insect already adapted to a warm coastal environment may therefore experience substantial physiological stress during heatwaves even if its average thermal tolerance appears high.

Temperature may influence mangrove insects through several mechanisms:

- Accelerated egg and larval development;
- Changes in adult emergence;
- Altered duration of larval and pupal stages;
- Changes in feeding and foraging activity;
- Increased metabolic demand;
- Reduced survival during thermal extremes;
- Altered fecundity;
- Changes in voltinism;
- Modification of species distributions.

Importantly, responses will differ among taxa. A highly mobile generalist may relocate or alter its activity period, whereas a host-specific herbivore or flower visitor may be constrained by the phenology and distribution of its mangrove host.

Thermal stress and physiological limitation

Temperature is one of the strongest determinants of insect performance. The most immediate direct impact of climate warming on insects is physiological. Moderate warming within an organism's physiological range can accelerate development and increase activity, but performance declines when temperatures approach upper limits. This produces a nonlinear response rather than a simple positive relationship between warming and insect abundance.

The vulnerability of tropical insects is particularly concerning. Deutsch *et al.* (2008) [9] proposed that many tropical ectotherms could experience greater warming risks than temperate species because tropical organisms frequently inhabit environments with relatively narrow seasonal thermal variation.

Bhagarathi & Maharaj (2023) [4] emphasized that climate change can influence insect growth, survival, development, reproduction, and population dynamics. This conclusion is particularly applicable to mangrove insects because coastal tropical environments can experience considerable daily variation between shaded and exposed microhabitats.

Holzmann *et al.* (2026) [14] provide particularly strong evidence for Neotropical vulnerability. Their field-based study found that lowland tropical insects possess limited thermal buffering and limited acclimation capacity. They also showed that thermal tolerance differed among orders and families; notably, Diptera generally showed relatively lower critical thermal maxima than aculeate Hymenoptera and Orthoptera.

For Neotropical mangrove insects, this finding has important implications. Mangrove forests occur primarily in warm lowland coastal regions where insects may already experience high ambient temperatures. During periods of reduced cloud cover, drought, low wind, or canopy loss, leaf, bark, sediment, and surface temperatures can exceed nearby meteorological averages. Thus, regional air-temperature projections alone may underestimate biologically relevant heat exposure.

This finding suggests that rising temperatures, which are associated with climate warming, could be a major factor that drive shifts in the composition of mangrove insect communities by favoring relatively heat-tolerant taxa over thermally sensitive taxa.

Table 2: Major climate-change drivers and their predicted effects on Neotropical mangrove insects

Climatic driver	Potential direct effect on insects	Potential indirect mangrove-mediated effect	Principal ecological consequence	Representative literature
Rising mean temperature	Alters metabolism, development, emergence and fecundity	Changes flowering timing and mangrove growth	Phenological shifts and altered population dynamics depending on thermal tolerance	Memmott *et al.* (2007) [19]; Deutsch *et al.* (2008) [9]; Hegland *et al.* (2009) [13]; Robinet & Roques (2010) [21]; Harvey *et al.* (2023) [12]; Holzmann *et al.* (2026) [14]
Heatwaves	Thermal stress and mortality; reduced activity beyond thermal optima	Can alter canopy microclimate and floral resource quality	Population decline and disruption of pollination	Hegland *et al.* (2009) [13]; Harvey *et al.* (2023) [12]; Holzmann *et al.* (2026) [14]
Altered rainfall	Changes humidity and freshwater availability	Modifies freshwater input, salinity and plant productivity	Shifts in insect abundance and breeding success	Alongi (2015) [2]; IPCC (2022) [15]; Harvey *et al.* (2023) [12]
Drought	Desiccation stress and reduced resource availability	Increased salinity and physiological stress in mangroves	Habitat filtering and altered community composition	Alongi (2015) [2]
Sea-level rise	Loss of suitable terrestrial or intertidal habitat	Changes mangrove zonation and forest distribution	Local population displacement or habitat loss	Alongi (2015) [2]; IPCC (2022) [15]; Saintilan *et al.* (2023) [22]
Increased inundation	Can affect eggs, larvae and soil-dwelling stages	Alters sediment oxygen and root-zone habitat	Reduced survival of vulnerable life stages	IPCC (2022) [15]
Salinity change	Osmoregulatory and physiological stress in susceptible taxa	Alters plant composition and habitat suitability	Community turnover and spatial redistribution	Alongi (2015) [2]; IPCC (2022) [15]; Saintilan *et al.* (2023) [22]
Hurricanes and storms	Direct mortality and displacement	Defoliation, flower loss and structural habitat damage	Rapid decline in pollinator diversity and visitation	Landry (2013b) [18]; IPCC (2022) [15]
Changing phenology	Alters emergence and seasonal activity	Shifts flowering and nectar / pollen availability	Mismatch between insect activity and floral resources	Memmott *et al.* (2007) [19]; Hegland *et al.* (2009) [13];
Seasonal change	Earlier, later or prolonged emergence and activity	Shifts in flowering and food availability	Phenological mismatch or altered synchrony	Robinet & Roques (2010) [21]; Harvey *et al.* (2023) [12]

The effects shown in Table 2 should not be interpreted as universally negative. Climate responses are expected to differ among species because of variation in body size, mobility, thermal tolerance, developmental stage, dispersal ability, host specificity, and behavioral flexibility. Nevertheless, the possibility that some species may benefit temporarily from warming does not eliminate broader biodiversity risks. Climate change can produce winners and losers simultaneously, resulting in substantial community reorganization even where total insect abundance does not immediately decline.

Altered Precipitation, Humidity, and Drought

1. Precipitation is particularly important in mangrove systems because rainfall affects both terrestrial microclimate and coastal hydrology. Freshwater input can reduce salinity, while prolonged drought may increase evaporative concentration of salts. Consequently, changes in precipitation can influence insects indirectly by modifying the salinity regime experienced by mangrove vegetation [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Humidity also affects insect water balance. Small-bodied insects are particularly vulnerable to desiccation because of their relatively high surface-area-to-volume ratios. Reduced humidity and prolonged dry conditions may therefore affect survival, egg viability, larval development, and daily activity patterns [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

For flower-visiting insects, precipitation may additionally alter foraging. Heavy rainfall can temporarily suppress flight activity, whereas changes in seasonal rainfall may influence flowering intensity and floral resource production. The ecological significance of this relationship is that insect abundance alone may not predict pollination effectiveness; the temporal overlap between suitable foraging conditions and flower availability is also critical [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

In the Neotropics, rainfall patterns are often strongly seasonal. Therefore, climate-driven changes in wet and dry season timing could shift insect population peaks relative to mangrove flowering periods. The magnitude and direction of these effects are likely to vary geographically, emphasizing the need for region-specific studies rather than assuming that a response documented in one mangrove system will occur identically elsewhere [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Sea-Level Rise, Inundation, Salinity, and Insect Habitat

Sea-level rise represents a major climate-related threat to coastal ecosystems. Mangroves may respond through landward migration, vertical sediment accretion, changes in species composition, or, where migration is prevented by coastal development, habitat loss. These processes are highly relevant to insects because insects depend on the structural and biological characteristics of mangrove forests [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

A reduction in mangrove area may result in:

- Loss of floral resources;
- Loss of foliage and host plants;
- Reduction in nesting or resting sites;
- Changes in canopy structure;
- Altered litter quantity and quality;
- Loss of decomposer habitat;
- Fragmentation of insect populations.

Changes in inundation frequency may be particularly important for immature stages. Insects whose eggs, larvae, pupae, or nesting structures occur in litter, bark, sediment, or low vegetation may experience increased mortality if flooding becomes more prolonged or unpredictable [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Salinity is also an important ecological filter. Although mangrove plants are adapted to saline conditions, many insects associated with them may not possess equivalent tolerance. Climate-related changes in freshwater discharge and evaporation can therefore alter the spatial distribution of insect communities along salinity gradients [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

The ecological consequences are likely to be highly species-specific. A generalist flying insect may respond mainly to changing floral resources, whereas a sedentary larval stage may be directly affected by inundation or sediment conditions [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Mangrove Flowering Phenology and Climate Change

Importance of Phenological Synchrony

In mangrove ecosystems, flowering timing determines when nectar, pollen, floral scent, and other reproductive resources become available to insect visitors. Insects also exhibit phenology through seasonal emergence, reproduction, migration, diapause, and changes in daily activity.

Plant-insect interactions are therefore dependent on synchrony. A mangrove may produce abundant flowers, but reproductive success may decline if effective insect pollinators are scarce during peak flowering. Conversely, an insect population may emerge during a period when floral resources are unavailable.

Climate warming can affect these two partners differently. Plants and insects may use different environmental cues, including air temperature, soil temperature, rainfall, photoperiod, tidal conditions, and resource availability. Consequently, even if both groups respond to warming, their rates and directions of response may differ.

Memmott *et al.* (2007) [19] identified climate-driven disruption of plant–pollinator interactions as an important ecological consequence of global warming. Hegland *et al.* (2009) [13] further emphasized that climate warming can affect phenology, abundance, and distribution of both plants and pollinators.

Evidence from Neotropical Mangroves

The importance of flowering overlap is clearly illustrated by *A. germinans* and *L. racemosa*. Landry (2013a) [17] found that *A. germinans* began flowering before *L. racemosa* and that flowering overlap varied among years. During co-flowering periods, *A. germinans* received substantially greater insect visitation, demonstrating that temporal overlap can influence competition for pollination services.

The implications under climate change are substantial. If warming or altered rainfall increases the overlap between the flowering periods of competing mangrove species, pollinator competition may intensify. Alternatively, if flowering periods become more separated, competition could decline but certain species may face periods of reduced pollinator availability.

Sánchez-Núñez & Mancera-Pineda (2012) [24] also demonstrated that the three major neotropical mangrove species that they studied differed in pollination specialization and fruit set. *R. mangle* showed ambophilous pollination and had one highly effective insect pollinator identified as *Copestylum* sp., whereas *A. germinans* had a more generalized system involving multiple effective pollinators. Such differences suggest that vulnerability to climate-mediated pollinator disruption may depend partly on the degree of interaction redundancy.

Table 3: Representative insect taxa associated with neotropical mangrove pollination and their relevance to climate sensitivity

Insect taxon	Order	Family	Mangrove association	Ecological role	Climate-change relevance	Author(s) & Year
Copestylum sp.	Diptera	Syrphidae	*Rhizophora mangle*	Highly effective pollinator	Altered temperature and phenology may affect adult activity and synchrony with flowering	Sánchez-Núñez & Mancera-Pineda (2012) [24]
Apis mellifera	Hymenoptera	Apidae	*Avicennia germinans* and *Laguncularia racemosa*	Most common floral visitor in the Florida study	Temperature and extreme weather may alter visitation and colony activity	Landry (2013a) [17]; Bhagarathi & Maharaj (2023) [4]
Palpada albifrons	Diptera	Syrphidae	*Laguncularia racemosa*	Pollinator assemblage member	Community response to severe disturbance may alter visitation	Landry (2013b) [18]; Bhagarathi & Maharaj (2023) [4]; Holzmann *et al.* (2026) [14]
Xylocopa virginica	Hymenoptera	Apidae	*Laguncularia racemosa*	Pollinator assemblage member	Large-bodied pollinator potentially affected by habitat and floral-resource changes	Landry (2013b) [18]
Euodynerus spp.	Hymenoptera	Vespidae	*Laguncularia racemosa*	Flower visitor/pollinator assemblage member	Sensitive to vegetation and nesting-resource changes	Landry (2013b) [18]
Sphex jamaicensis	Hymenoptera	Sphecidae	*Laguncularia racemosa*	Flower visitor/pollinator assemblage member	May be affected by storm disturbance and habitat restructuring	Landry (2013b) [18]
Bees, wasps, flies and butterflies (multiple taxa)	Hymenoptera, Diptera, Lepidoptera	Multiple families	*A. germinans* and *L. racemosa*	Pollinator assemblage	Changes in phenology may alter visitation and competition between co-flowering mangroves	Landry (2013a) [17]
Multiple insect flower visitors (25 species recorded)	Three orders	Twelve families	*R. mangle*, *L. racemosa*, *A. germinans*	Visitors ranging from effective pollinators to possible pollen/nectar exploiters	Taxonomic diversity may provide interaction redundancy, but individual climate responses remain poorly resolved	Sánchez-Núñez & Mancera-Pineda (2012) [24]

Table 3 distinguishes species-level identifications from broader taxonomic categories. One major gap in the neotropical literature is that many mangrove insect visitors remain identified only to family, genus, or functional group.

Development, reproduction, and population dynamics

Climate warming can modify the rate at which insects progress through egg, larval, pupal, and adult stages. Faster development may initially increase the number of generations per year for some species. However, accelerated development does not necessarily increase population fitness. Exposure to high temperatures can reduce survival, adult size, fertility, and reproductive success [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

In mangrove ecosystems, these responses may be complicated by tidal cycles. A species may experience favorable temperatures during one portion of the day but heat exposure, inundation, salinity, or reduced oxygen availability during another. The interaction between climate and tidal ecology is therefore a major research priority [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

The findings of Holzmann *et al.* (2026) [14] are particularly relevant because they indicate that thermal responses differ strongly among insect orders and families. Consequently, predictions based on a single "average insect" response are scientifically inappropriate. Closely related species may also differ in their capacity for acclimation or behavioral thermoregulation.

Phenological shifts

Climate warming can alter insect phenology by changing developmental rates and environmental cues. Robinet & Roques (2010) [21] identified earlier flight periods and accelerated development among major responses to warming, while Harvey *et al.* (2023) [12] emphasized that phenological responses can disrupt ecological interactions.

For mangrove insects, phenological change may affect:

- Pollinator emergence relative to flowering;
- Herbivore activity relative to new leaf production;
- Parasitoid emergence relative to host availability;
- Decomposition relative to seasonal litterfall; and
- Predator activity relative to prey abundance.

Phenological disruption may be especially important in tropical coastal systems where flowering and insect activity are influenced by multiple variables rather than temperature alone. Rainfall, salinity, tidal cycles, photoperiod, and freshwater input may all influence biological timing. Therefore, climate change could alter synchrony without necessarily producing a simple advancement or delay.

Phenological Mismatch as a Central Climate Risk

Phenological mismatch is one of the most important conceptual mechanisms through which climate change may affect mangrove insects. It occurs when interacting species change the timing of biological events at different rates [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

A simplified sequence may occur as follows:

Climate warming or altered rainfall → changed mangrove flowering cue → earlier, delayed, shorter, or prolonged flowering → different response by insect emergence or activity → reduced temporal overlap → altered visitation → reduced pollen transfer → changes in fruit set and genetic exchange.

The consequences may extend beyond a single reproductive season. Repeated reductions in cross-pollination may influence population genetic structure, particularly where a mangrove species depends strongly on animal-mediated outcrossing.

For *L. racemosa*, this issue is especially relevant because reduced insect visitation may alter the balance between outcrossing and selfing. Landry (2013a) [17] demonstrated that reduced visitation affected the mating consequences of flowering overlap. Therefore, climate-induced changes in pollinator abundance or activity could potentially influence not only seed production but also the genetic mating system.

Phenological mismatch should not, however, be assumed automatically. Some plant–pollinator interactions may remain synchronized, and generalist pollination systems may be buffered by multiple alternative visitors. The extent of vulnerability depends on interaction specificity, phenological flexibility, local climate, and the availability of alternative resources.

Extreme Weather Events and Mangrove Insect Communities

Hurricanes as Ecological Disturbances

Hurricanes and tropical storms are major natural disturbances in many neotropical mangrove regions. They can remove foliage, damage branches, alter canopy structure, destroy flowers, redistribute sediments, and change insect habitat almost immediately [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Landry (2013b) [18] provides particularly important evidence from Florida. Following hurricanes, pollinator species richness associated with *L. racemosa* was reduced by approximately 43-65%, while pollinator diversity declined by approximately 36–70%. Insect visitation also declined, and this reduction was associated with lower outcrossing frequencies. Although the study examined the ecological effects of hurricanes rather than attributing those hurricanes to anthropogenic climate change, it provides a valuable mechanistic example of how increasingly severe climatic disturbances could affect mangrove pollination systems.

The eventual return of visitation rates demonstrates ecological resilience, but recovery was not necessarily identical to the pre-disturbance condition. The composition and foraging behavior of the insect community changed, indicating that numerical recovery alone may not represent complete functional recovery [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Climate Change and Extreme-Event Risk

Climate change assessments project increasing risks to coastal ecosystems from sea-level rise, coastal flooding, and climate-related extremes [15]. For mangrove insects, the ecological significance of extreme events depends on both the frequency of disturbance and the time available for recovery.

Repeated disturbances could potentially produce cumulative effects such as:

1. Storm damages to vegetation;
2. Decline in insect abundance;
3. Reduced pollination;
4. Altered mangrove reproduction;
5. Interaction networks become progressively simplified.

Such cumulative effects may be particularly important in fragmented mangrove landscapes where insect populations cannot easily recolonize disturbed habitat.

Canopy Disturbances

Defoliation, branch loss, mortality, and sediment disturbance may immediately affect insects' dependent upon foliage, flowers, bark, or shaded microhabitats.

Some insect populations may recover rapidly because of short generation times and high dispersal capacity. However, repeated disturbance can prevent communities from returning to previous states. The frequency of disturbance is therefore as important as the severity of individual events [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Repeated canopy damage could also increase microclimatic exposure by reducing shade. This creates a potentially important feedback:

Climate extreme → canopy loss → increased habitat temperature → additional thermal stress on insects.

Such feedbacks remain poorly studied in mangrove entomology.

Table 4: Ecological consequences of climatic disturbances across insect functional groups in mangrove ecosystems

Insect functional group	Representative insect orders/families or species	Principal climate-related exposure	Documented or expected biological response	Potential consequence for mangrove ecosystem functioning	Key supporting authors and year(s)
Pollinators	Hymenoptera: Apidae, Vespidae, Sphecidae; including *Apis mellifera*, *Xylocopa virginica*, *Sphex jamaicensis*, and *Euodynerus* spp.	Rising temperature, altered flowering phenology, hurricanes, and severe storms	Changes in pollinator abundance, visitation frequency, foraging behaviour, species richness, diversity, and temporal overlap with flowering	Reduced or altered pollen transfer; changes in outcrossing and mating systems; potential effects on fruit and propagule production	Hegland *et al.* (2009); Sánchez-Núñez & Mancera-Pineda (2012) [24], Landry (2013a, 2013b) [17, 18]
Fly pollinators	Diptera: Syrphidae; including *Copestylum* sp. 1 and *Palpada albifrons*	Temperature change, altered floral-resource availability, and extreme disturbances	Potential changes in adult activity, visitation patterns, abundance, and synchrony with mangrove flowering; pollinator assemblages may change following disturbance	Altered pollination efficiency, particularly where syrphid flies are effective or highly effective pollinators	Hegland *et al.* (2009) [13]; Sánchez-Núñez & Mancera-Pineda (2012) [24]; Landry (2013b) [18]
Specialized or relatively low-redundancy pollinator systems	*Copestylum* sp. 1 (Syrphidae) associated with *Rhizophora mangle*; other effective pollinator taxa associated with *Laguncularia racemosa* and *Avicennia germinans*	Climatic changes affecting insect phenology, abundance, distribution, or habitat	Loss or decline of important pollinator taxa may reduce effective pollen transfer where relatively few taxa perform major pollination functions	Potential reduction in reproductive success and recruitment; disruption of specialized plant–pollinator interactions	Hegland *et al.* (2009) [13]; Sánchez-Núñez & Mancera-Pineda (2012) [24]
Generalized pollinator assemblages	Multiple Hymenoptera, Diptera, and Lepidoptera flower visitors	Warming, altered precipitation, and shifts in flowering overlap	Different pollinator species may respond differently to climatic changes, potentially causing assemblage turnover while maintaining or reducing functional redundancy	Changes in pollination-network composition; possible buffering where alternative effective pollinators remain available	Hegland *et al.* (2009) [13]; Sánchez-Núñez & Mancera-Pineda (2012) [24]
Herbivorous insects	Lepidoptera, Coleoptera, and Hemiptera; species-specific mangrove herbivores remain insufficiently documented in climate-focused neotropical studies	Warming, heat extremes, drought, altered rainfall, and climate-mediated changes in host-plant quality	Changes in developmental rate, phenology, feeding activity, survival, distribution, and population abundance are biologically plausible and consistent with broader climate–insect literature	Altered leaf damage, mangrove productivity, plant stress, and interactions with predators and parasitoids	Hegland *et al.* (2009) [13]; Sánchez-Bayo & Wyckhuys (2019) [23]
Detritivores and litter-associated insects	Primarily Diptera and Coleoptera; taxonomic representation remains poorly resolved in neotropical mangrove climate literature	Altered temperature, inundation, sediment conditions, salinity, and changes in litter production	Potential changes in immature-stage survival, decomposition activity, distribution, and seasonal abundance	Changes in litter fragmentation, decomposition processes, nutrient cycling, and detrital food webs	Alongi (2015) [2]; Sánchez-Bayo & Wyckhuys (2019) [23]
Predatory insects	Predatory Coleoptera and Hemiptera, including potential Carabidae and Reduviidae representatives	Temperature change, altered habitat structure, and climate-driven changes in prey abundance or phenology	Potential shifts in predator activity, distribution, phenology, and predator–prey synchrony	Changes in biological regulation of herbivorous and other insect populations; altered trophic interactions	Hegland *et al.* (2009) [13]; Sánchez-Bayo & Wyckhuys (2019) [23]
Parasitoids	Hymenoptera and Diptera parasitoids	Temperature-mediated changes in host development and emergence; altered seasonal conditions	Potential temporal mismatch between parasitoids and their hosts; changes in development and host exploitation	Reduced or altered biological control of herbivores and subsequent changes in mangrove insect community structure	Hegland *et al.* (2009) [13]; Sánchez-Bayo & Wyckhuys (2019) [23]
Immature, sediment-, litter-, or water-associated insects	Larvae and pupae of Diptera and other insects utilizing wet substrates, litter, sediment, or periodically inundated microhabitats	Sea-level rise, increased inundation, salinity shifts, flooding, and altered sediment oxygen conditions	Potential mortality, displacement, altered emergence timing, and changes in habitat suitability	Changes in recruitment to adult populations and disruption of detrital and food-web processes	Alongi (2015) [2]; IPCC (2022) [15]
Whole pollinator communities following extreme events	Multi-species assemblages including *A. mellifera*, *P. albifrons*, *X. virginica*, *Euodynerus* spp., and *S. jamaicensis*	Hurricanes and severe tropical storms	In Florida mangrove communities, hurricanes were followed by reductions of approximately 43–65% in pollinator species richness	Reduced outcrossing in *Laguncularia racemosa* and changes in foraging patterns, demonstrating that severe disturbance can alter both	Landry (2013b) [18]

			and 36–70% in pollinator diversity; insect visitation also declined	community composition and plant reproductive processes	
Plant–pollinator systems affected by phenological change	Multiple insect pollinator taxa interacting with flowering mangroves, including *Rhizophora mangle*, *Laguncularia racemosa*, and *Avicennia germinans*	Warming and altered climatic cues affecting insect activity and flowering	Advancement, delay, or altered duration of flowering and insect appearance may create temporal mismatches, although responses vary among species	Reduced synchrony may alter visitation rates, pollen transfer, mating patterns, fruit set, and long-term plant recruitment	Hegland *et al.* (2009) [13]; Sánchez-Núñez & Mancera-Pineda (2012) [24]; Landry (2013a) [17];
Mangrove insect communities as a whole	Hymenoptera, Diptera, Coleoptera, Lepidoptera, Hemiptera, and other under-sampled taxa	Interacting effects of warming, rainfall change, salinity, sea-level rise, habitat transformation, and extreme events	Community turnover, shifts in abundance and distribution, altered phenology, and changes in ecological interactions are expected, but direct long-term evidence remains limited for many neotropical mangrove systems	Potential changes in pollination, herbivory, decomposition, trophic regulation, and overall mangrove ecosystem resilience	Hegland *et al.* (2009) [13]; Alongi (2015) [2]; Sánchez-Bayo & Wyckhuys (2019) [23]; IPCC (2022) [15]

Evidence specifically demonstrating climate-change responses of individual insect species within neotropical mangrove ecosystems remains limited. Consequently, studies by Sánchez-Núñez & Mancera-Pineda (2012) [24] and Landry (2013b) [18] synthesize direct mangrove evidence with broader mechanistic evidence on climate-sensitive insect and plant–pollinator responses. Table 4 distinguishes documented disturbance responses from expected or mechanistically supported climate responses. The species-specific evidence for neotropical mangrove pollination is especially strong for *Rhizophora mangle, Laguncularia racemosa,* and *Avicennia germinans*. The hurricane-associated evidence from *Laguncularia racemosa*, for example, is directly documented by Landry (2013b) [18], whereas broader climate-driven phenological responses are reported by Hegland *et al.* (2009) [13].

Climate Effects on Herbivorous Insects

Climate change may also alter herbivory in mangrove forests. Herbivorous insects can respond to temperature directly through changes in developmental rate and feeding activity and indirectly through changes in host-plant physiology [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Warming may increase the metabolic requirements of some herbivores, potentially increasing consumption when temperatures remain within physiological limits. However, heat stress can also reduce feeding or survival. Drought and salinity may alter leaf chemistry, nutritional quality, toughness, and defensive compounds, thereby affecting herbivore performance [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

The consequences for mangrove ecosystems are potentially complex. Increased herbivory could reduce leaf area and photosynthetic capacity, while climate stress may simultaneously reduce the capacity of mangroves to replace damaged tissues. Conversely, extreme conditions could reduce populations of specialized herbivores [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

One of the most important research gap is therefore the absence of sufficient long-term, species-level studies linking climatic records with mangrove herbivore abundance and actual plant damage in neotropical forests.

Detritivores, Decomposers, and Climate Change

Mangrove ecosystems are characterized by substantial organic matter production. Leaf litter, wood, and detrital material support complex decomposer communities. Insect detritivores may contribute directly to fragmentation and breakdown of organic material and interact with microbial decomposers [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Climate change can influence this functional group through:

- Temperature-dependent metabolic changes;
- Altered litter production;
- Storm-generated woody debris;
- Flooding frequency;
- Sediment oxygen conditions;
- Salinity change.

These processes may produce opposing responses. Warmer temperatures may increase biological activity under favorable conditions, whereas excessive heat, drought, salinity, or prolonged inundation may reduce survival [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

This functional group remains particularly under-studied in Neotropical mangrove climate research. Pollination studies are valuable, but focusing exclusively on pollinators risks overlooking other insect-mediated processes that contribute to ecosystem functioning [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Predators, Parasitoids, and Climate-Mediated Food-Web Change

Insect populations in mangroves are regulated by multiple biotic interactions. Predatory insects may consume herbivores, while parasitoids regulate host populations. Climate change can disrupt these relationships when predators, parasitoids, and prey respond differently to temperature and seasonal conditions [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

A parasitoid may emerge before or after the period of greatest host availability. Similarly, a predator may experience reduced prey availability if warming changes, the timing of herbivore outbreaks [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Therefore, climate impacts may propagate through trophic levels. A change initially affecting one insect group can influence others through food-web interactions. For example: Temperature change → altered herbivore emergence → altered predator/parasitoid synchrony → changed herbivore regulation → increased or reduced mangrove damage.

The complexity of these indirect pathways reinforces the need to investigate entire insect communities rather than studying individual taxa in isolation.

Pollination Networks, Competition, and Functional Redundancy

A key question in climate ecology is whether biodiversity provides resilience through functional redundancy. A mangrove flower visited by several effective insect taxa may be less vulnerable to the temporary loss of one species than a flower dependent on a narrow set of pollinators [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

The findings of Sánchez-Núñez & Mancera-Pineda (2012) [24] suggest differences in pollination specialization among major Neotropical mangroves. *A. germinans* exhibited a relatively generalized system with multiple effective pollinators, whereas *R. mangle* had fewer identified highly effective pollinators.

However, generalization does not necessarily guarantee resilience. Multiple insect species may still respond similarly to a common climatic stressor. For example, widespread heat stress or severe hurricane disturbance may reduce several members of the pollinator community simultaneously [2, 4, 5, 8, 10, 11, 12, 13, 21, 23].

Competition between plant species is also relevant. Landry (2013a) [17] demonstrated that flowering overlap between *A. germinans* and *L. racemosa* affected pollinator visitation. Therefore, climate-induced shifts in flowering schedules could restructure plant–pollinator networks by changing the temporal overlap among competing floral resources.

Conceptual Framework

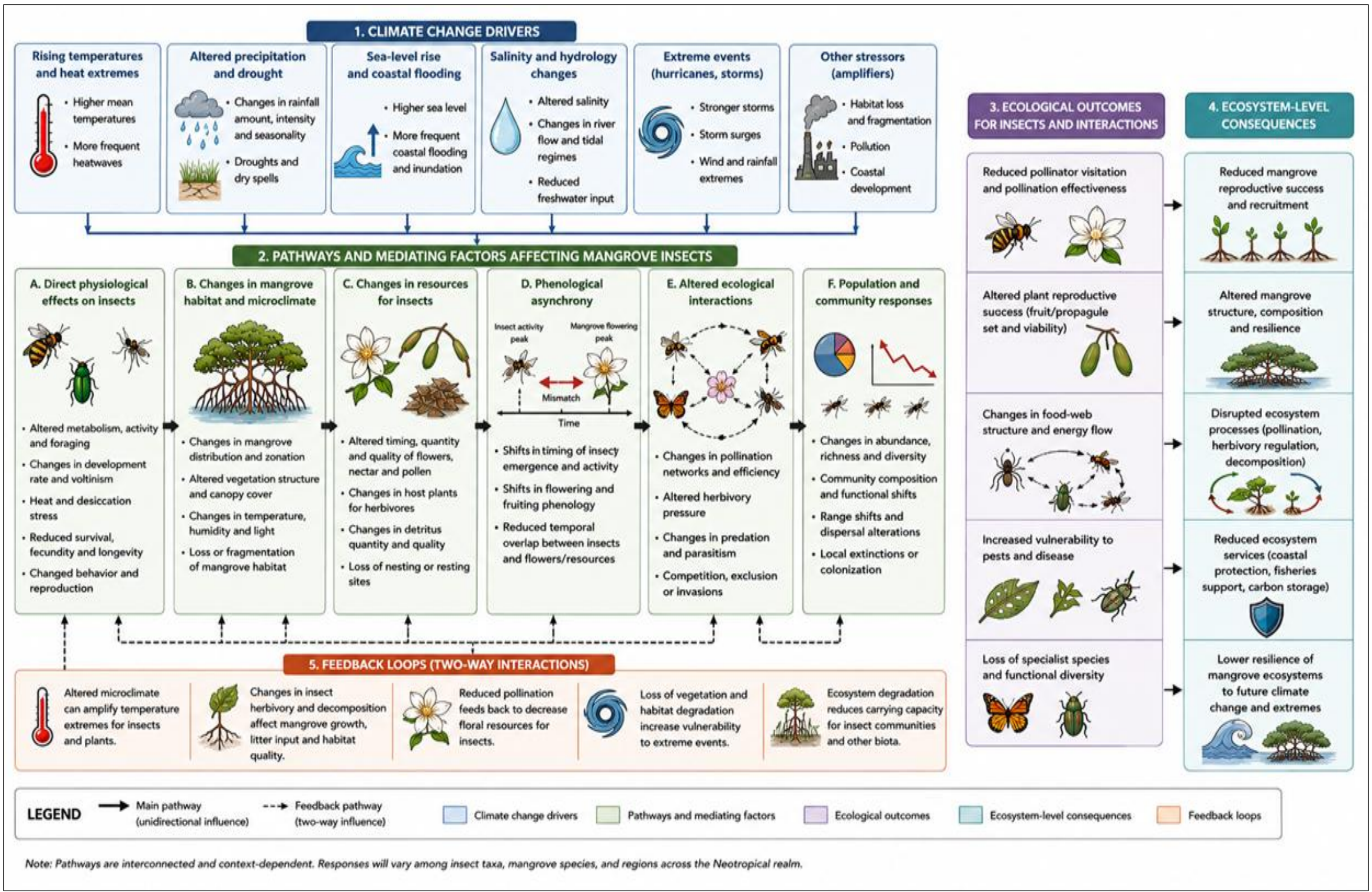

Fig 2: Conceptual pathways linking climate change to neotropical mangrove insects

The conceptual model (Figure 2) presents climate change as a primary driver acting through four major pathways: warming and heat extremes; rainfall and drought shifts; sea-level rise and salinity change; and storms and extreme events. These climatic exposures affect insect physiology, mangrove flowering phenology, habitat and microclimate, and ecological interactions. The intermediate responses may ultimately alter population abundance, species distributions, phenological synchrony, pollination, mangrove recruitment, genetic connectivity, food-web stability, and ecosystem resilience.

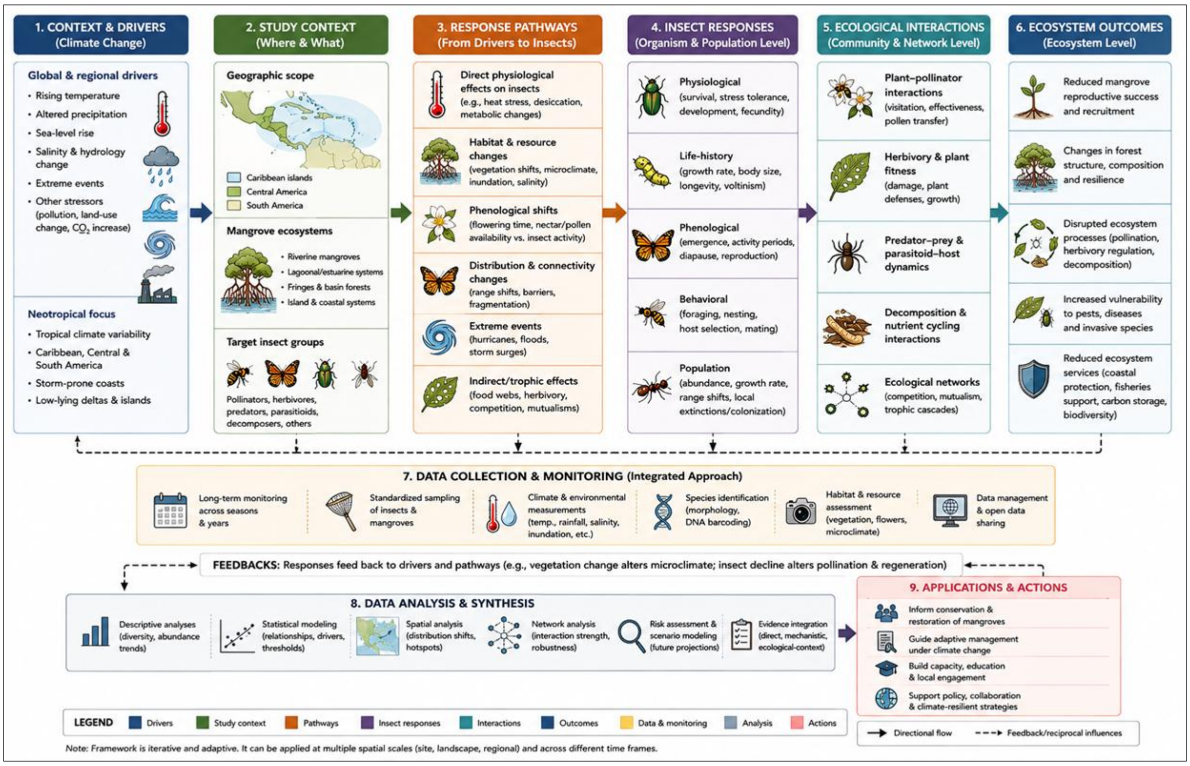

Fig 3: Research framework for assessing climate impacts on neotropical mangrove insects

The research framework (Figure 3) integrates climatic exposure, biological response, and ecological consequences with long-term monitoring. It also identifies three major gaps requiring attention: taxonomic gaps, geographic gaps, and management gaps.

Geographic Research Gaps in the Neotropics

The Neotropics contain extensive mangrove habitat, yet research effort is geographically uneven [5, 6, 7, 17]. Florida and some Caribbean locations have contributed important studies of mangrove pollination, hurricanes, and flowering interactions. However, substantially less is known about insect communities across many regions of Central America, the Guianas, northern Brazil, and other South American mangrove systems. This geographic bias presents several problems.

First, climatic conditions vary substantially across the Neotropics. Results from subtropical Florida cannot simply be transferred to equatorial Guyana or Amazonian mangrove systems.

Second, mangrove species composition varies geographically. A climate response involving *A. germinans* and *L. racemosa* may differ from one involving *R. racemosa*, *A. schaueriana*, or *Pelliciera rhizophorae*.

Third, the insect fauna varies geographically. A pollinator community may contain different species even when the same mangrove host occurs in two regions.

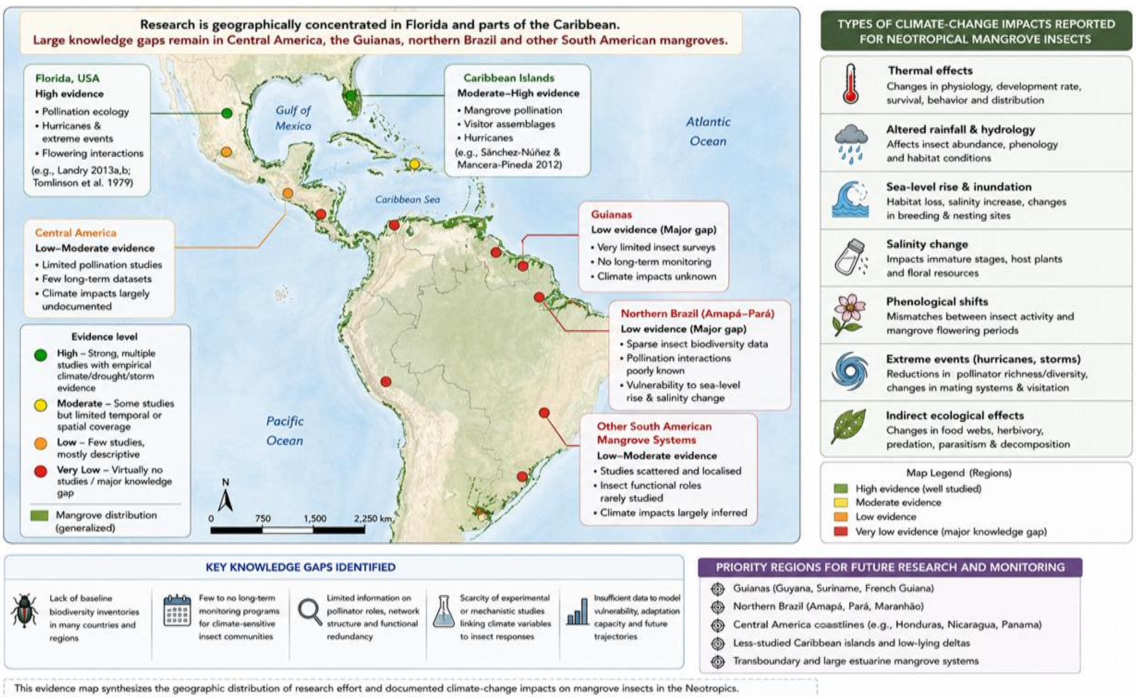

Fig 4: Evidence map for climate-change impacts on Neotropical mangrove insects

Figure 4. presents an evidence map for climate-change impacts on Neotropical mangrove insects. The literature reviewed similarly identify a pronounced need for baseline biodiversity assessment and long-term study in under-researched Caribbean and South American locations.

Guyana and Northern South America as Research Priorities

Guyana provides an important opportunity for advancing entomological studies because its coastal mangrove ecosystems occur within a region where climate change, sea-level rise, coastal erosion, freshwater discharge, and seasonal climatic variation may interact.

Important research priorities include:

- Establishing baseline inventories of mangrove-associated insects;
- Identifying insects to the lowest possible taxonomic level;
- Determining which flower visitors are effective pollinators rather than merely visitors;
- Monitoring flowering phenology of dominant mangrove species;
- Measuring insect abundance across wet and dry seasons;
- Simultaneously recording temperature, humidity, rainfall, salinity, tidal inundation, and light intensity;
- Investigating effects of extreme rainfall, drought, flooding, and coastal storms;
- Using dna barcoding to improve identification of poorly known taxa;
- Comparing natural and disturbed mangrove sites;
- Developing long-term climate–insect datasets.

A major scientific contribution from such studies would be the transition from descriptive biodiversity inventories toward mechanistic climate ecology.

Major Knowledge Gaps

Table 5 identifies major knowledge gaps, limitations and recommended research priority.

Table 5: Major knowledge gaps and recommended research priorities

Knowledge gap	Current limitation	Recommended research priority
Direct climate-change evidence	Few long-term studies directly link climatic trends to mangrove insect population change	Establish multi-year climate-insect monitoring programs
Species-level identification	Many insects remain identified only as morphospecies or broad groups	Use expert taxonomy, reference collections and DNA barcoding
Geographic bias	Limited studies in many Caribbean and South American mangrove systems	Expand studies into Guyana, the Guianas, Central America and Brazil
Pollinator effectiveness	Flower visitation is often incorrectly equated with pollination	Measure pollen deposition, fruit set and seed production
Phenological data	Few simultaneous datasets for flowering and insect activity	Monitor plants and insects over complete annual cycles
Extreme events	Limited pre- and post-disturbance datasets	Develop rapid-response ecological monitoring after storms
Non-pollinator insects	Herbivores, decomposers and parasitoids are poorly represented	Include multiple functional groups in biodiversity assessments
Physiological mechanisms	Limited thermal and salinity tolerance data for mangrove insects	Conduct thermal-performance and tolerance experiments
Network ecology	Few complete mangrove insect interaction networks	Construct quantitative plant-insect networks
Climate adaptation	Limited integration of insects into mangrove restoration planning	Incorporate insect biodiversity and phenology into restoration design

Conservation and Management Implications

Mangrove conservation should not focus exclusively on tree cover. A mangrove forest may retain substantial vegetation while experiencing reductions in ecological interaction diversity. Pollinator loss, altered herbivore regulation, or disruption of decomposer communities may reduce ecosystem function before major vegetation decline becomes apparent.

Climate-resilient mangrove management should therefore consider:

Protection of Habitat Heterogeneity

Mangroves containing variation in canopy cover, tree age, species composition, elevation, and hydrological conditions may support a greater diversity of insect microhabitats. Maintaining this heterogeneity may increase opportunities for ecological buffering.

Landscape Connectivity

Connectivity may facilitate recolonization after storms and other disturbances. Isolated fragments may be more vulnerable if insect populations are unable to recover through immigration.

Protection of Floral Resources

Restoration projects should consider whether restored mangrove stands provide temporally continuous floral resources and whether pollinator populations are present.

Long-Term Monitoring

Single-season surveys cannot determine whether observed differences represent normal seasonal variation or climate-driven change. Long-term monitoring is essential.

Integration of Insects into Restoration Evaluation

Restoration success should be evaluated using biological indicators in addition to tree survival. These indicators could include insect richness, functional diversity, pollinator visitation, herbivory, decomposition activity, and phenological synchrony.

Table 6 provides conservation and research actions that may benefit conservation and management efforts.

Table 6: Recommended conservation and research actions

Priority action	Rationale	Expected benefit
Protect intact mangrove forests	Maintains habitat complexity and microclimatic buffering	Supports diverse insect communities and ecological functions
Maintain hydrological connectivity	Allows natural sediment and water processes	Increases mangrove resilience to climate and sea-level change
Preserve landward migration corridors	Enables mangroves to respond spatially to sea-level rise	Reduces habitat compression and supports insect movement
Establish long-term insect monitoring	Detects trends before local losses become irreversible	Improves climate-risk assessment
Measure microclimate	Regional weather stations may not represent insect-level exposure	Provides biologically relevant temperature and humidity data
Integrate DNA barcoding	Improves identification of cryptic and poorly known taxa	Strengthens biodiversity baselines
Monitor plant–insect phenology	Detects changes in temporal synchrony	Identifies risks to pollination and herbivory
Include insects in restoration assessments	Vegetation survival alone does not demonstrate ecosystem recovery	Evaluates functional restoration
Protect habitat mosaics	Different insect taxa require different resources and microhabitats	Maintains functional and taxonomic diversity
Reduce non-climatic stressors	Climate risks interact with fragmentation and pollution	Increases overall ecosystem resilience
Develop Guyana-specific datasets	Addresses a major regional information gap	Supports locally appropriate conservation policy

The reviewed literature supports the conclusion that climate change can influence Neotropical mangrove insects through a combination of direct and indirect pathways. The strongest conceptual framework is not one in which climate acts directly on insects alone but one in which insects are embedded within a changing mangrove ecosystem.

Temperature affects insect physiology while also affecting plant phenology. Rainfall affects insect activity while also modifying freshwater input and salinity. Sea-level rise changes mangrove distribution and habitat structure. Storms directly disturb insects while simultaneously altering flowers, canopy structure, and resource availability. These interacting pathways create the potential for cascading ecological effects.

A particularly important finding is that mangrove reproductive ecology can be sensitive to changes in insect communities. Sánchez-Núñez & Mancera-Pineda (2012) [24] demonstrated differences in pollination effectiveness and specialization among major Neotropical mangrove species. Landry (2013a) [17] demonstrated that flowering overlap can affect competition for pollinators, while Landry (2013b) [18] showed that hurricane disturbance can substantially reduce pollinator richness and diversity and influence outcrossing. Together, these studies provide strong evidence that mangrove-insect interactions are dynamic and sensitive to environmental change.

However, caution is necessary when attributing all observed changes to climate change. A hurricane effect is not automatically evidence of anthropogenic climate change, and seasonal changes in insect abundance do not automatically represent a warming response. The most important methodological requirement for future research is therefore the integration of long-term biological observations with climatic measurements.

The taxonomic gap is equally important. Climate vulnerability cannot be assessed accurately when insect communities are represented only by categories such as “bees,” “flies,” or “beetles.” Different species within the same family may differ greatly in thermal tolerance, dispersal capacity, host specificity, and phenological flexibility.

Future Neotropical mangrove research should integrate traditional field sampling with molecular identification, trait-based ecology, physiological experiments, remote sensing, and long-term environmental monitoring.

5. Conclusion

This review demonstrates that climate change has the potential to affect Neotropical mangrove insects through a complex combination of direct physiological stress and indirect ecological changes. Rising temperatures, altered rainfall regimes, prolonged droughts, sea-level rise, changing salinity and inundation patterns, and increasingly disruptive extreme weather events can influence insect development, survival, abundance, distribution, behaviour, and seasonal activity. However, the most significant ecological effects are likely to arise from the interaction between climatic change and mangrove ecosystem processes. Insects do not respond to climate change independently; their responses are closely linked to changes in mangrove habitat structure, flowering phenology, food availability, hydrology, and interactions with other organisms.

For the Neotropical region, the available literature suggests that climate vulnerability will not be uniform across countries or mangrove systems. The Neotropics contain substantial environmental heterogeneity, ranging from relatively seasonal Caribbean mangroves and hurricane-prone coastal forests to equatorial mangrove systems influenced by high rainfall, major river discharge, and extensive tidal processes. Consequently, findings obtained from Florida, Mexico, or individual Caribbean locations cannot automatically be generalized to the entire region. This is particularly important because existing research remains geographically concentrated, whereas the attached review literature identifies the Caribbean and South American regions as requiring additional baseline inventories and long-term research on mangrove insect communities and their environmental drivers.

The evidence reviewed for Neotropical mangroves further indicates that changes in insect communities may have consequences extending beyond insect biodiversity. Insect pollinators contribute to the reproductive success of major mangrove species, while other insects participate in herbivory, decomposition, predation, and trophic regulation. Studies of *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa*, for example, demonstrate that insect assemblages, flowering overlap, pollinator competition, and mating systems are ecologically interconnected. Therefore, a climate-driven change in insect abundance or seasonal activity may potentially cascade through mangrove ecosystems by altering pollination, fruit and propagule production, genetic exchange, recruitment, and ultimately forest resilience.

Particular Implications for Guyana

The conclusions of this review are especially relevant to Guyana. Guyana's coastal mangrove ecosystems occur within the wider Neotropical region but possess environmental conditions that justify dedicated investigation rather than reliance on evidence from other countries. Guyana's low-lying coast is influenced by tropical climatic conditions, seasonal rainfall variation, tidal processes, freshwater influences, and coastal environmental change. These factors may interact to produce climate-related effects on mangrove insects that differ substantially from those documented in subtropical Florida and other Caribbean mangrove systems.

A central analytical finding of this review is that Guyana represents both a potentially vulnerable and a scientifically important knowledge gap. The available mangrove insect literature is much stronger for selected pollination systems in other parts of the Neotropics than for comprehensive, long-term climate-linked insect studies in Guyanese mangroves. The guiding review similarly emphasizes the limited understanding of insect diversity, abundance, and pollinator interactions in Guyanese and other under-researched mangrove systems and highlights the importance of establishing baseline ecological information.

This lack of baseline information presents a major challenge. Without reliable data on which insect species currently occur in Guyana's mangroves, their seasonal abundance, host associations, and relationships with mangrove flowering, it will be difficult to determine whether future changes represent normal seasonal variation or genuine climate-driven ecological change. In other words, the absence of baseline biodiversity data limits the ability to detect climate impacts. Establishing the present composition and ecological functioning of mangrove insect communities should therefore be regarded as a prerequisite for assessing future climate vulnerability.

For Guyana, one of the most important potential mechanisms requiring investigation is climate-mediated phenological mismatch. Changes in rainfall and temperature could affect both mangrove flowering and insect activity, but not necessarily at the same rate. If insect pollinators become active before, after, or outside periods of peak flowering, the temporal overlap necessary for effective pollination could decline. This may be particularly important for mangrove species whose reproductive success depends substantially on insect visitation. Conversely, the review's evidence also suggests that generalized pollination systems containing multiple insect taxa may possess some degree of functional buffering. Determining whether Guyanese mangroves are supported by specialized or functionally redundant insect pollinator communities is therefore an important research priority.

Another important consideration is the interaction between climate change, coastal change, and habitat connectivity. In Guyana and other parts of the Neotropics, mangrove forests should not be viewed simply as isolated stands of vegetation. They function as connected coastal habitats whose insect populations may depend on the movement of organisms among mangrove patches, adjacent forests, wetlands, agricultural landscapes, and other coastal environments. Climate-related habitat loss, sea-level change, erosion, or fragmentation could therefore reduce insect dispersal and recolonization capacity following environmental disturbances. The consequences may be particularly serious for small or isolated mangrove fragments.

At the wider Neotropical scale, the review indicates that climate change may produce different ecological winners and losers. Highly mobile, generalist insects with broad environmental tolerances may be capable of adjusting their distributions or exploiting alternative floral resources. In contrast, specialized pollinators, host-specific herbivores, insects with narrow thermal tolerances, and taxa dependent on particular mangrove microhabitats may be more vulnerable. This suggests that climate change could alter not only total insect abundance but also community composition and functional structure. A mangrove ecosystem may therefore retain a numerically abundant insect community while losing particular ecological functions if specialized pollinators, decomposers, predators, or parasitoids decline.

The review also highlights the importance of extreme climatic disturbances for the Neotropics. Hurricane-associated changes in pollinator richness, diversity, and mating patterns documented elsewhere provide a warning that sudden disturbances can rapidly restructure insect–plant interactions. For the broader Caribbean and Neotropical region, increasing attention should therefore be directed toward both gradual climatic change and episodic disturbances. The ecological question should not only be whether insects recover, but also whether they recover to their original species composition and functional state. A community that returns numerically after disturbance may still differ in pollination efficiency, trophic interactions, and resilience.

Overall, the evidence suggests that Guyana and the wider Neotropical region should be considered priorities for integrated climate-mangrove-insect research. Future investigations should simultaneously measure insect diversity and abundance, species composition, flowering phenology, temperature, humidity, rainfall, salinity, tidal inundation, and habitat characteristics. Such studies should extend across multiple seasons and years because short-term surveys cannot adequately separate seasonal fluctuations from longer-term climate-driven trends.

In conclusion, the greatest concern for Guyana and the Neotropics is not simply that climate change may reduce insect numbers. Rather, climate change may reorganize the timing, composition, distribution, and ecological interactions of insect communities. This reorganization could affect pollination, mangrove reproduction, herbivore regulation, decomposition, and food-web stability before obvious changes in forest cover become visible. For Guyana, the immediate scientific priority should therefore be to establish robust baseline data on mangrove-associated insects and their interactions with dominant mangrove species. For the wider Neotropical region, greater geographic coverage and standardized long-term monitoring are required to identify regional patterns of vulnerability and resilience.

Ultimately, understanding the response of neotropical mangrove insects to climate change will be essential for understanding the future resilience of mangrove ecosystems themselves. Protecting mangrove forests in Guyana and across the Neotropics should consequently involve not only conserving mangrove trees and coastal area but also maintaining the insect communities and ecological interactions that support mangrove reproduction, recovery, and long-term ecosystem functioning.

6. Recommendations

Based on the findings of this review, the following recommendations are made:

1. Establish long-term monitoring sites across representative neotropical mangrove regions to collect simultaneous biological and climatic data.
2. Prioritize under-studied regions, particularly Guyana, the Guianas, northern South America, and less-studied Caribbean mangrove systems.
3. Conduct species-level insect inventories rather than relying exclusively on broad taxonomic categories.
4. Use DNA barcoding and morphological taxonomy together to improve identification of cryptic and poorly known mangrove insects.
5. Monitor mangrove flowering and insect activity simultaneously to detect phenological shifts and potential mismatches.
6. Distinguish flower visitors from effective pollinators through pollen-load analysis, pollen deposition studies, exclusion experiments, and fruit-set measurements.
7. Include multiple insect functional groups, particularly herbivores, decomposers, predators, and parasitoids, rather than focusing exclusively on bees and other pollinators.
8. Develop before-and-after disturbance datasets to evaluate the effects of hurricanes, flooding, drought, and other extreme events.
9. Measure physiological tolerance, including thermal and salinity tolerance, of representative mangrove-associated insect species.
10. Integrate insect biodiversity into mangrove restoration programs, including monitoring of ecological interactions as indicators of restoration success.
11. Protect habitat connectivity to facilitate insect recolonization and ecological recovery after climatic disturbances.
12. Develop regional climate-biodiversity databases that combine standardized insect sampling with meteorological, hydrological, and vegetation information.
13. Apply quantitative ecological network analysis to identify highly connected or functionally important insect taxa.
14. Promote interdisciplinary research linking entomology, mangrove ecology, climatology, hydrology, molecular biology, and conservation science.

Compliance with ethical standard

1. Credit Authorship Contribution Statement

Lakhnarayan Kumar Bhagarathi- Conceptualization, methodology, literature search and screening, data curation, formal analysis, writing - original draft, writing - review and editing.

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

4. Disclosure of conflict of interest

The author certify that this submission is original work and is not under review at any other publication. The authors hereby declare that this manuscript does not have any conflict of interest.

5. Statement of informed consent

The author declare that informed consent was obtained from all individual participants included in the study. All work utilized in this study was fully cited and referenced so authors of prior researches are given their due credentials for their work.

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