



Impact of Climate Change on Insect Diversity and Species Distribution in Natural Ecosystems

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Abstract

Background: Accelerating climate change poses an unprecedented threat to global biodiversity, with insects serving as critical ecological indicators due to their sensitivity to environmental shifts.

Objective: This study examines the measurable impacts of climate change on insect diversity and geographic species distribution across temperate and tropical natural ecosystems.

Methods: We integrated long-term field survey datasets (1990–2023), remote sensing outputs, and species distribution models (SDMs) from 47 monitored sites to assess changes in species richness, Shannon diversity indices, and habitat suitability scores.

Results: Species richness declined by 16.9% and habitat suitability by 21.8% relative to baseline. Mean poleward range shifts of 42.3 km and phenological mismatches averaging 8.7 days were documented. High-altitude and thermophilic species showed accelerated range expansions, while cold-adapted specialists faced disproportionate extinction risk.

Conclusion: Climate change is demonstrably restructuring insect communities at ecologically significant rates, with cascading implications for pollination, nutrient cycling, and food web stability. Urgent policy-integrated conservation strategies are imperative.

Keywords: climate change, insect biodiversity, species distribution, habitat suitability, phenological mismatch, conservation ecology

1. Introduction

Climate change has emerged as the defining ecological challenge of the twenty-first century, fundamentally altering the biophysical conditions upon which species depend ^[1]. Rising global mean temperatures, shifting precipitation regimes, and the increasing frequency of extreme weather events collectively reconfigure habitat quality and resource availability across terrestrial and aquatic ecosystems ^[2]. Among the taxa most acutely sensitive to these changes, insects occupy a uniquely critical position—both as ecological actors (pollinators, decomposers, and primary consumers) and as reliable bioindicators of ecosystem health ^[3].

Mounting evidence documents widespread insect population declines globally. A landmark meta-analysis reported a 45% reduction in insect abundance over 40 years across monitored sites in diverse biomes ^[4]. These trends carry profound implications for ecosystem services valued at trillions of dollars annually, including crop pollination and biological pest suppression ^[5]. However, the mechanistic pathways through which specific climate variables drive distributional and diversity changes remain incompletely understood, particularly across heterogeneous landscapes ^[6].

This article synthesises empirical findings from long-term ecological monitoring to quantify the impact of climate change on

insect species richness, diversity, and distribution, providing an evidence-based framework for conservation planning.

2. Related Work

Parmesan and Yohe ^[7] first demonstrated statistically robust poleward and elevational range shifts attributable to twentieth-century warming across diverse taxonomic groups, establishing foundational evidence for climate-driven biogeographic change. Subsequent studies refined these analyses for insects specifically, identifying differential vulnerability among orders—with Lepidoptera and Odonata showing the most pronounced distributional responses ^[8]. Warren *et al.* ^[9] demonstrated that species failing to track climate velocity—the rate at which suitable climatic conditions migrate across the landscape—face heightened extinction risk. Phenological asynchrony has been studied extensively by Thackeray *et al.* ^[10], who documented that plant flowering and insect emergence are diverging at ecologically significant rates. Thomas *et al.* ^[11] projected that 15–37% of species could be committed to extinction by 2050 under mid-range climate scenarios, with insects disproportionately represented in high-sensitivity guilds.

3. Climate Change–Biodiversity Interaction Framework

We conceptualise climate–insect interactions through a multi-pathway framework. Primary abiotic drivers—temperature increase, precipitation variability, and extreme event frequency—act directly on insect physiology (thermal tolerance limits, desiccation resistance) and indirectly through host plant and prey phenology ^[12]. Secondary effects include habitat fragmentation, which constrains dispersal capacity and reduces effective population sizes, thereby amplifying extinction risk under shifting climate envelopes. Species distribution models (SDMs) integrate these drivers to project future habitat suitability. Ensemble SDM approaches, combining MaxEnt, Boosted Regression Trees, and

Generalised Additive Models, reduce individual model uncertainty and improve spatial prediction accuracy ^[13]. Diversity metrics—species richness, Shannon diversity index, and functional diversity—serve as response variables capturing community-level restructuring.

4. Materials and Methods

4.1. Study Sites and Data Sources

Data were compiled from 47 long-term ecological monitoring sites spanning temperate (n=28) and tropical (n=19) biomes across South Asia, Western Europe, and East Africa. Insect survey records from 1990 to 2023 were sourced from national biodiversity databases, peer-reviewed literature, and standardised Malaise trap and transect count protocols ^[14].

4.2. Climate Variables

Temperature anomalies were derived from ERA5 reanalysis data. Precipitation indices (Standardised Precipitation Index, SPI) and extreme event counts (days exceeding 35°C) were extracted at 0.25° spatial resolution. Atmospheric CO₂ concentrations were obtained from NOAA Global Monitoring Laboratory records.

4.3. Statistical Analysis

Temporal trends in species richness and diversity were assessed using generalised linear mixed models (GLMMs) with site as a random effect. Ensemble SDMs were calibrated using 70% training and 30% validation data splits. Range shift magnitudes were calculated as the distance between historical (1990–2000) and contemporary (2013–2023) centroid locations for each species.

5. Results and Comparative Analysis

Table 1 summarises the relationships between key climate change factors and biodiversity impacts, including associated severity indices derived from meta-analytic weighting.

Table 1: Climate Change Factors and Biodiversity Impacts

Climate Factor	Primary Mechanism	Biodiversity Impact	Severity Index
Rising Temperature	Phenological mismatch	Range shifts poleward	High (0.7–0.9)
Altered Precipitation	Habitat moisture loss	Species richness decline	Moderate–High (0.5–0.8)
Extreme Events	Habitat destruction	Local extinction risk	Very High (>0.9)
CO ₂ Increase	Plant phenology shift	Herbivore–plant decoupling	Moderate (0.4–0.6)
Habitat Fragmentation	Connectivity loss	Reduced gene flow	High (0.6–0.8)

Severity Index: 0–0.3 Low; 0.3–0.6 Moderate; 0.6–0.9 High; >0.9 Very High. Source: Compiled from meta-analytic datasets.

Species richness declined by 16.9% relative to the 1990–2000 baseline, while mean range shifts of 42.3 km northward and eastward were recorded. Phenological mismatch—the temporal gap between peak insect emergence and host-plant

flowering—increased from 2.1 to 8.7 days. Table 2 presents key distribution and diversity indicators across temporal windows.

Table 2: Species Distribution Indicators Across Temporal Windows

Indicator	Baseline (1990–2000)	Current (2010–2023)	Projected (2050)
Species Richness Index	0.89	0.74 (-16.9%)	0.55–0.62
Shannon Diversity Index	3.21	2.87 (-10.6%)	2.40–2.60
Habitat Suitability Score	0.78	0.61 (-21.8%)	0.38–0.50
Mean Range Shift (km)	Baseline	+42.3 km N/E	+90–140 km
Phenological Mismatch (days)	2.1 ± 0.4	8.7 ± 1.2	14–22 days

Values represent site-aggregated means ± SE. Projected values are ensemble SDM medians (RCP 6.0 scenario).

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