

MINI REVIEW

El Niño and Indian Insect Biodiversity: Understanding Climate Variability and its Ecological Consequences

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Abstract

El Niño, the warm phase of the El Niño-Southern Oscillation (ENSO), is a major driver of global climate variability, influencing temperature, rainfall, and extreme weather events worldwide. In India, El Niño is commonly associated with weakened southwest monsoon rainfall, higher temperatures, and prolonged dry spells, with important implications for agriculture and biodiversity. As ectothermic organisms, insects are highly sensitive to climatic fluctuations, which affect their distribution, phenology, survival, and species interactions. Climatic anomalies associated with El Niño can alter insect community structure by promoting outbreaks of certain pest species while adversely affecting beneficial insects such as pollinators and natural enemies. These changes may disrupt ecosystem functioning and reduce the resilience of agricultural and natural ecosystems. This article summarizes the mechanisms of El Niño, its influence on the Indian climate, and its potential consequences for Indian insect biodiversity. It also highlights key research gaps and emphasizes the need for long-term monitoring and climate-informed conservation and pest management strategies in the face of increasing climate variability.

Key words: El Niño; ENSO; Indian monsoon; insect biodiversity; climate variability; climate change; insect ecology; ecosystem services.

Introduction

India is recognized as one of the world's megadiverse countries, harboring an extraordinary variety of insects that contribute significantly to ecosystem functioning, agricultural productivity, and biodiversity conservation. More than 63,000 insect species have been described from India, representing nearly 6-7% of the world's known insect fauna, although many species remain undocumented, particularly from biodiversity-rich regions such as the Himalaya, Western Ghats, North-East India and the Andaman and Nicobar

Islands (Chandra & Gupta, 2013; Zoological Survey of India, 2023). These insects perform indispensable ecological functions including pollination, decomposition, nutrient recycling, biological control of pests, and maintenance of food webs, thereby supporting both natural ecosystems and agricultural landscapes.

The distribution, abundance and seasonal activity of insects are closely linked to climatic conditions. Since insects are ectothermic organisms, their growth, survival, reproduction and dispersal depend largely on environmental temperature,

rainfall and humidity (Bale *et al.*, 2002). Even small changes in climate can influence the timing of insect emergence, alter species interactions, and modify population dynamics. Consequently, climatic variability has become one of the most important factors shaping insect biodiversity in the twenty-first century.

Among the various climate phenomena influencing weather patterns across the globe, El Niño is one of the most significant. Although it originates in the tropical Pacific Ocean, El Niño influences atmospheric circulation on a global scale, resulting in altered rainfall patterns, increased temperatures, droughts, floods and extreme weather events in many parts of the world, including India (Trenberth, 1997; IPCC, 2023). In India, El Niño is widely known for its association with weaker southwest monsoons, reduced rainfall and prolonged dry spells, all of which can have profound consequences for agriculture and biodiversity.

Insects respond rapidly to these environmental changes because of their short life cycles and high reproductive potential. Some species may benefit from warmer and drier conditions by increasing their populations or expanding their geographical range, whereas others may decline because of habitat degradation, reduced host plant availability or changes in humidity. Such responses can alter ecological interactions, influence pollination services, disrupt natural biological control and increase the incidence of insect pests in agricultural ecosystems (Deutsch *et al.*, 2018; Wagner, 2020). With climate change expected to increase the frequency and intensity of extreme weather events, understanding the ecological consequences of El Niño has become increasingly important.

For India, where agriculture and biodiversity

are closely linked to monsoon rainfall, studying the influence of El Niño on insect diversity is essential for developing climate-resilient conservation strategies, strengthening pest forecasting systems, and safeguarding the ecosystem services provided by insects. This article provides an overview of El Niño, explains its relationship with the Indian climate, and discusses its potential impacts on Indian insect biodiversity and the challenges ahead.

El Niño: Causes, Characteristics, and Global Climate Effects

Weather and climate are among the most important environmental factors influencing insect life. Seasonal rainfall, temperature, humidity and wind patterns determine where insects occur, how rapidly they develop, when they reproduce and how they interact with plants and other organisms. One of the most important natural climate phenomena affecting global weather is El Niño, which periodically alters atmospheric circulation and influences weather patterns across many parts of the world, including India (Trenberth, 1997).

The term El Niño, meaning “*The Little Boy*” or “*Christ Child*” in Spanish, was first used by fishermen along the coasts of Peru and Ecuador in South America. They observed that every few years, around Christmas, the normally cold waters of the eastern Pacific Ocean became unusually warm, resulting in a sharp decline in fish catches because nutrient-rich cold water no longer reached the ocean surface. This unusual warming event was later recognized as part of a large-scale ocean-atmosphere phenomenon known as the El Niño–Southern Oscillation (ENSO) (McPhaden *et al.*, 2020).

ENSO is a naturally occurring climate cycle comprising three phases:

- **El Niño:** the warm phase, characterized by

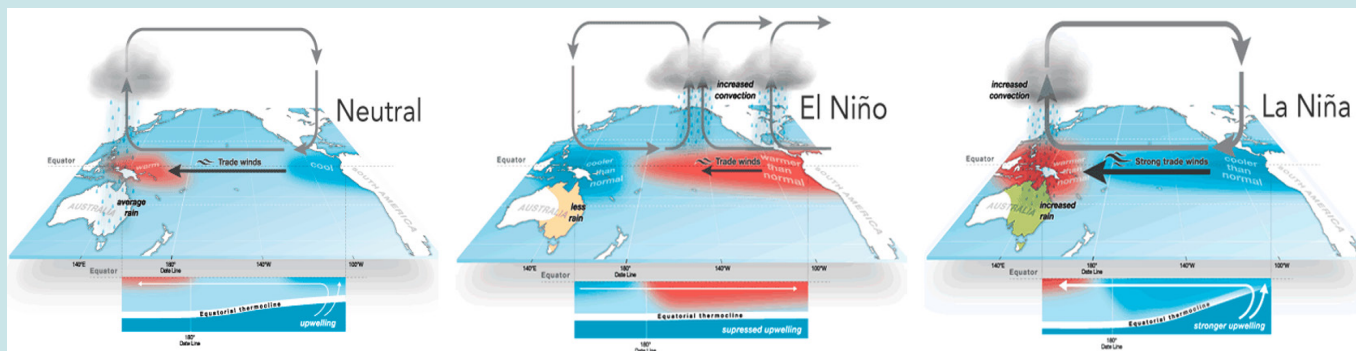


Figure 1. Neutral, El Niño and La Niña conditions in the equatorial Pacific.

Source: Adapted from the International Research Institute for Climate and Society (IRI), Columbia University, ENSO Essentials. (Available at: <https://iri.columbia.edu/our-expertise/climate/enso/enso-essentials/>)

above-average sea surface temperatures in the central and eastern equatorial Pacific Ocean.

- **La Niña:** the cool phase, characterized by below-average sea surface temperatures in the same region.
- **Neutral phase:** when oceanic and atmospheric conditions remain close to their long-term average.

These phases occur irregularly every 2 to 7 years, and each event usually lasts 9-12 months, although some may persist for more than a year depending on oceanic and atmospheric interactions (NOAA, 2024).

Under normal conditions, strong easterly trade winds blow across the tropical Pacific Ocean, pushing warm surface water towards Indonesia and northern Australia. As warm water accumulates in the western Pacific, cold, nutrient-rich water rises from deeper layers along the western coast of South America through a process known as upwelling. This upwelling supports highly productive marine ecosystems and one of the world's richest fisheries. Warm waters in the western Pacific also promote cloud formation and heavy rainfall over Southeast Asia and northern Australia.

During an El Niño event, the trade winds

weaken or sometimes reverse. As a result, warm surface water moves eastward towards the central and eastern Pacific Ocean, while the upwelling of cold water along the South American coast becomes weaker. These changes alter the exchange of heat and moisture between the ocean and the atmosphere, disrupting normal atmospheric circulation known as the Walker Circulation. Consequently, rainfall patterns shift across the globe, causing floods in some regions and droughts in others (Trenberth, 1997; McPhaden *et al.*, 2020).

Although El Niño develops in the Pacific Ocean, its effects extend far beyond the Pacific through atmospheric teleconnections, whereby changes in one region influence weather in distant parts of the world. This explains why a warming event occurring thousands of kilometres away can influence the Indian monsoon, African droughts, Australian bushfires, South American floods and even cyclone activity in different ocean basins (IPCC, 2023).

It is important to note that El Niño is a natural climatic phenomenon and should not be confused with climate change. El Niño has existed for thousands of years as part of Earth's natural climate system. However, global warming caused by increasing greenhouse gas concentrations may intensify the impacts of El Niño by raising

background temperatures and increasing the frequency of extreme weather events. Recent climate projections suggest that strong El Niño events may become more frequent under future climate scenarios, potentially amplifying their effects on agriculture, biodiversity and water resources (Cai *et al.*, 2015).

For India, El Niño is particularly significant because it often influences the strength of the southwest monsoon, which supplies nearly three-fourths of the country's annual rainfall. Variations in monsoon rainfall caused by El Niño can directly affect crop production, freshwater availability, forest ecosystems and insect populations. Since insects respond rapidly to changes in temperature and moisture, understanding the mechanisms behind El Niño is essential for predicting changes in insect biodiversity and developing effective conservation and pest-management strategies.

El Niño and the Indian monsoon: Why does it matter to India?

India's climate, agriculture and biodiversity are closely linked to the southwest monsoon, which contributes nearly 75-80% of the country's annual rainfall between June and September. The timing, distribution and intensity of monsoon rainfall determine water availability, crop production, forest productivity and the survival of countless plant and animal species. Among the various climatic factors influencing the Indian monsoon, El Niño has received considerable scientific attention because of its potential to weaken monsoon circulation and alter rainfall patterns (Gadgil & Gadgil, 2006; Kumar *et al.*, 2006).

Although El Niño develops in the equatorial Pacific Ocean, changes in sea surface temperature influence atmospheric circulation over the Indian Ocean through large-scale teleconnections.

During many El Niño years, the rising warm air and associated rainfall shift eastwards towards the central Pacific, weakening the atmospheric circulation that normally supports the southwest monsoon over the Indian subcontinent. Consequently, several parts of India experience below-normal rainfall, delayed monsoon onset, prolonged dry spells, and higher-than-average temperatures (Rasmusson & Carpenter, 1983; IPCC, 2023).

Historically, several severe droughts in India have coincided with strong El Niño events. For example, the El Niño years 1982-83, 1987, 2002, 2009, 2015-16 and 2023 were associated with rainfall deficits in many parts of the country, although the intensity of their impacts varied among regions (IMD, 2024). Reduced rainfall during these years affected agricultural production, reservoir storage, groundwater recharge and natural ecosystems. However, it is equally important to recognize that not every El Niño results in drought in India, and not every drought is caused by El Niño.

The relationship between El Niño and the Indian monsoon has become increasingly complex because other climatic systems also influence rainfall. One such important factor is the Indian Ocean Dipole (IOD), which refers to differences in sea surface temperature between the western and eastern Indian Ocean. During a positive IOD, warmer waters in the western Indian Ocean can enhance moisture transport towards India and partly compensate for the adverse effects of El Niño. Therefore, the final outcome depends on the combined influence of ENSO, IOD, regional atmospheric circulation and local weather systems (Saji *et al.*, 1999; Ashok *et al.*, 2001).

Besides reducing rainfall, El Niño often leads to higher surface temperatures across many parts of India. Increased temperatures accelerate

soil moisture loss through evaporation, intensify drought conditions and impose physiological stress on crops and natural vegetation. Water scarcity also affects flowering, fruiting and leaf production, which in turn influences herbivorous insects, pollinators and natural enemies. Thus, the ecological consequences of El Niño extend well beyond rainfall deficits and include widespread changes in terrestrial and freshwater ecosystems.

The effects of El Niño are not uniform across India. Northwestern and central India often experience stronger drought conditions, whereas some southern and northeastern regions may receive near-normal or even above-normal rainfall depending on regional weather patterns. Such geographical variation creates different ecological responses among insect communities, making long-term monitoring essential for understanding climate–biodiversity relationships.

For agriculture, changes in rainfall timing may be as important as changes in total rainfall. Delayed monsoon onset can postpone sowing, alter crop growth stages and modify the availability of host plants for insects. Similarly, prolonged dry periods followed by sudden heavy rainfall may create favourable conditions for certain pest species while adversely affecting beneficial insects such as pollinators and parasitoids. Consequently, climate variability influences not only insect abundance but also the complex ecological interactions among crops, insects and their natural enemies (Deutsch *et al.*, 2018).

Recent seasonal forecasting by the India Meteorological Department (IMD) has significantly improved the country's ability to predict El Niño events several months in advance. These forecasts are increasingly used by agricultural agencies to develop contingency plans, advise farmers on crop management and strengthen pest surveillance

programmes. Integrating climate forecasts with entomological observations will become increasingly important for anticipating insect outbreaks and conserving biodiversity under changing climatic conditions.

In summary, El Niño does not merely influence rainfall; it alters the entire environmental framework within which insects live. Changes in temperature, humidity, vegetation and water availability ultimately determine how insect populations respond. Understanding this climate–monsoon–insect relationship is therefore fundamental to assessing the future of India's insect biodiversity.

Indian Insect Biodiversity: Diversity, Distribution and Ecological Importance

India is one of the world's 17 megadiverse countries, supporting an extraordinary diversity of plants, animals and microorganisms. Its remarkable geographical variation, ranging from the snow-covered Himalayas to tropical rainforests, deserts, grasslands, wetlands, mangroves and island ecosystems, provides a wide array of habitats that support an exceptionally rich insect fauna. Although insects are often overlooked because of their small size, they represent the largest and most diverse group of animals in the country and play indispensable roles in maintaining ecological balance.

According to the Zoological Survey of India (ZSI), more than 63,000 insect species have been described from India, accounting for nearly half of the country's faunal diversity. However, entomologists estimate that the actual number is considerably higher, as many species, particularly those inhabiting tropical forests, high-altitude ecosystems and soil habitats, remain undiscovered or undescribed (Chandra & Gupta, 2013; ZSI, 2023).

Every year, numerous new insect species and new distributional records are reported from different parts of the country, indicating that India's insect diversity is still incompletely known.

The country's four global biodiversity hotspots-the Himalaya, Western Ghats-Sri Lanka, Indo-Burma (including North-East India) and the Nicobar Islands (part of Sundaland) harbour an exceptionally high number of endemic insect species. These regions possess unique climatic conditions, vegetation types and ecological niches that have promoted insect diversification over millions of years. Many species found in these hotspots occur nowhere else in the world and are therefore particularly vulnerable to habitat degradation and climate change.

Insects occupy almost every terrestrial and freshwater habitat in India. Butterflies and bees are abundant in forests and agricultural landscapes, dragonflies and damselflies thrive in wetlands and river ecosystems, termites dominate tropical soils, while beetles, ants, flies, moths, grasshoppers and true bugs perform a wide variety of ecological functions. Their abundance and diversity make insects one of the most important components of Indian biodiversity.

Beyond their remarkable diversity, insects provide numerous ecosystem services that are essential for both natural ecosystems and human society. Pollinating insects such as honey bees, solitary bees, butterflies, moths, hoverflies and beetles contribute significantly to the reproduction of flowering plants and many economically important crops. Approximately 75% of global food crops benefit, at least partly, from animal-mediated pollination, with insects contributing the largest share of this service (IPBES, 2016). In India, crops such as mustard, sunflower, apple, mango, cucurbits, cardamom and several vegetables

depend substantially on insect pollination.

Insects also play a vital role in biological control by naturally suppressing populations of agricultural pests. Ladybird beetles, lacewings, praying mantids, predatory bugs, spiders and parasitoid wasps help regulate pest populations, reducing the need for chemical pesticides. Similarly, dung beetles, termites and numerous fly larvae accelerate the decomposition of organic matter, improve soil fertility and facilitate nutrient recycling. Aquatic insects contribute to freshwater ecosystem functioning by participating in decomposition, nutrient cycling and serving as food for fish and amphibians.

Despite their ecological importance, many insect populations are experiencing increasing pressure from habitat loss, pesticide use, pollution, invasive species and climate change. Among these factors, climatic variability is particularly significant because insects are ectothermic organisms whose physiology, growth, development and reproduction are directly influenced by environmental temperature and moisture (Bale *et al.*, 2002). Even relatively small changes in climate may alter their distribution, abundance and seasonal activity. India's diverse climatic zones further complicate insect responses to changing weather. Species adapted to cool Himalayan environments may decline under rising temperatures, whereas insects inhabiting arid and semi-arid regions may expand their geographical range. Likewise, prolonged droughts, irregular rainfall and heat waves associated with El Niño can alter flowering periods, host plant availability and freshwater habitats, ultimately affecting numerous insect groups simultaneously.

Understanding the richness and ecological significance of Indian insect biodiversity is therefore essential for appreciating how climate phenomena

such as El Niño may influence ecosystems. Since insects form the foundation of many terrestrial and freshwater food webs, changes in their diversity can have cascading effects on birds, reptiles, amphibians, mammals and ultimately human well-being. Conserving insect diversity is not only important for protecting wildlife but also for ensuring sustainable agriculture, food security and ecosystem resilience in a changing climate.

How does El Niño affect Indian Insect biodiversity?

Insects are among the first organisms to respond to changes in climate because they are ectothermic, meaning that their body temperature and physiological activities depend largely on the surrounding environment. Temperature, rainfall, humidity and seasonal weather patterns directly influence insect survival, reproduction, development, dispersal and interactions with host plants. Consequently, climatic anomalies associated with El Niño can substantially alter insect communities across India's diverse ecosystems (Bale *et al.*, 2002; Parmesan, 2006; Ramaiah *et al.*, 2022). The effects of El Niño on insects are rarely uniform. While some species may benefit from warmer temperatures and prolonged dry conditions, others may decline because of habitat degradation, reduced food availability or disruption of their life cycles. The overall impact depends on the ecological requirements of individual species and the intensity and duration of climatic changes.

Climate is one of the principal factors determining where insects can survive. During El Niño years, above-average temperatures and altered rainfall patterns may create favourable conditions for some insects to expand into new geographical areas, while others may disappear from regions that become unsuitable. Several insect species are already showing shifts in their

geographical distribution in response to changing climatic conditions. In India, insects inhabiting cooler Himalayan ecosystems may gradually move to higher elevations, whereas species adapted to warmer climates may extend their range into northern states or higher altitudes. Such shifts may alter local biodiversity, introduce new pest species into agricultural systems and change interactions among insects, plants and natural enemies (Parmesan, 2006; Chen *et al.*, 2011). Changes in insect distribution are particularly important for conservation because many endemic species occupying restricted habitats may have limited opportunities to migrate when climatic conditions become unfavourable.

Alteration of Life Cycles and Seasonal Activity

One of the earliest biological responses to climatic variability is a change in phenology, the seasonal timing of biological events such as emergence, mating, migration and reproduction.

Higher temperatures during El Niño often accelerate insect development, causing adults to emerge earlier than usual. Some species may complete their life cycle more rapidly and produce additional generations within a single year, whereas others may experience shortened adult longevity under prolonged heat stress (Bale *et al.*, 2002; Ramaiah *et al.*, 2022). Changes in seasonal activity can disrupt synchrony between insects and their environment. For example, herbivorous insects may emerge before their host plants produce sufficient foliage, while pollinating insects may become active before flowering begins. Such mismatches reduce survival, reproductive success and ecosystem stability (Forrest, 2016).

Effects on Pollinators

Pollinating insects are highly sensitive

to climatic fluctuations because their survival depends on the availability of flowering plants throughout the year. El Niño-induced droughts frequently reduce flowering intensity, nectar production and pollen availability, resulting in food shortages for bees, butterflies, moths, hoverflies and beetles (Potts *et al.*, 2010). India supports more than 700 species of bees, including the well-known honey bees (*Apis* spp.) and numerous solitary bees that contribute significantly to crop pollination. Declines in pollinator abundance may reduce the productivity of crops such as mustard, sunflower, apple, mango, cucurbits, cardamom and several vegetables. Butterflies may also be affected because prolonged dry periods reduce the availability of larval host plants and nectar sources. Changes in flowering time may further disrupt the close relationship between butterflies and flowering plants, affecting both pollination and butterfly reproduction.

Effects on Agricultural Insects

Agricultural landscapes often experience rapid changes in insect populations following climatic disturbances. Warm temperatures associated with El Niño generally accelerate insect growth and reproduction, while drought-stressed crops may become more vulnerable to insect attack. In India, fluctuations in temperature and rainfall have been linked with outbreaks of aphids, whiteflies, thrips, stem borers, planthoppers and several lepidopteran pests in different cropping systems (Deutsch *et al.*, 2018; Ramaiah *et al.*, 2022). Delayed monsoon onset or irregular rainfall can alter sowing dates and crop growth stages, influencing the availability of suitable host plants and changing pest population dynamics. Conversely, some insects requiring moist environments may decline during prolonged drought, demonstrating that climate change can benefit certain species

while adversely affecting others.

Effects on Natural Enemies

Predators and parasitoids provide valuable ecosystem services by naturally regulating populations of agricultural pests. However, these beneficial insects are often more sensitive to climatic variability than the pests they suppress. High temperatures and reduced humidity may decrease the survival and reproductive success of parasitoid wasps, lacewings, ladybird beetles and predatory bugs. Similarly, entomopathogenic fungi that infect insect pests require high humidity for successful transmission and therefore become less effective during prolonged dry conditions. Disruption of these natural biological control mechanisms may allow pest populations to increase rapidly, increasing dependence on chemical pesticides (Hance *et al.*, 2007; Ramaiah *et al.*, 2022).

Effects on Forest and Aquatic Ecosystems

India's forests support an enormous diversity of insects, many of which remain poorly studied. Drought conditions associated with El Niño may alter forest vegetation, reduce leaf production and increase tree stress, affecting herbivorous insects as well as their predators and parasitoids. Freshwater ecosystems are equally vulnerable. Reduced rainfall lowers water levels in rivers, streams, ponds and wetlands, affecting dragonflies, damselflies, mayflies, caddisflies and numerous other aquatic insects whose immature stages depend on freshwater habitats. These insects are important indicators of ecosystem health, and their decline may signal broader environmental degradation.

Ecological Consequences

Changes in insect biodiversity extend far beyond individual species. Since insects occupy multiple trophic levels, alterations in their

abundance can affect entire ecosystems. Reduced pollinator populations may lower seed production in wild and cultivated plants, while declines in decomposer insects can slow nutrient cycling. Similarly, changes in herbivore abundance may influence vegetation structure, and reductions in prey insects may affect birds, reptiles, amphibians and mammals that depend on them for food. Recent studies suggest that repeated climatic extremes can simplify insect communities by favouring a few climate-tolerant species while reducing populations of specialized and habitat-restricted insects (Harvey *et al.*, 2023). Such changes may ultimately reduce ecosystem resilience and biodiversity.

Why Long-Term Monitoring is Essential?

Although the influence of El Niño on Indian agriculture has been extensively studied, its effects on insect biodiversity remain comparatively underexplored. India lacks long-term nationwide monitoring programmes for many insect groups, making it difficult to distinguish natural population fluctuations from climate-driven changes. Regular biodiversity surveys, museum collections, DNA barcoding, ecological monitoring and citizen science initiatives such as butterfly and dragonfly monitoring programmes can generate valuable information on changing insect distributions and population trends. Integrating these observations with climate data will improve our understanding of how El Niño and future climate change are reshaping India's insect biodiversity.

Implications for Agriculture, Biodiversity Conservation and Future Preparedness

The influence of El Niño on Indian insect biodiversity extends beyond changes in species abundance and distribution. Because insects play fundamental roles in pollination, biological

control, decomposition and nutrient cycling, any climate-induced alteration in their populations can have cascading effects on agriculture, natural ecosystems and human well-being. Understanding these impacts is therefore essential for developing effective conservation strategies and strengthening climate resilience.

Implications for Indian Agriculture

Agriculture remains one of the sectors most vulnerable to climatic variability. During El Niño years, reduced and erratic rainfall often delays sowing, affects crop growth and modifies the availability of host plants for insect herbivores. Such changes can alter the timing of pest outbreaks, making them more difficult to predict and manage. Warmer temperatures may accelerate insect development, allowing some pest species to complete additional generations within a cropping season. At the same time, drought-stressed crops become physiologically weaker and more susceptible to insect attack. However, prolonged drought may also reduce the populations of insects that depend on moist habitats, demonstrating that climate effects differ among species and cropping systems (Deutsch *et al.*, 2018).

Climate variability also affects beneficial insects. Pollinators may experience food shortages due to reduced flowering, while predators and parasitoids that naturally regulate pest populations may decline under adverse environmental conditions. Consequently, the balance between pests and their natural enemies may be disturbed, increasing the risk of pest outbreaks and greater reliance on chemical insecticides. These observations highlight the importance of integrating weather forecasts with pest surveillance so that farmers can adopt timely management practices and reduce unnecessary pesticide applications.

Conservation of Indian Insect Biodiversity

India's insect diversity is closely associated with its forests, grasslands, wetlands, agricultural landscapes and biodiversity hotspots. Climatic disturbances such as prolonged droughts, heat waves and irregular rainfall can alter these habitats, affecting both common and rare insect species. Particular attention should be given to endemic insects occurring in the Western Ghats, the Himalayas and North-East India, where many species occupy narrow ecological niches and may be unable to adapt rapidly to changing climatic conditions. Conserving natural habitats, restoring degraded ecosystems and maintaining ecological connectivity will improve the resilience of insect populations to future climate variability.

Pollinator conservation deserves special attention because bees, butterflies, hoverflies and other flower-visiting insects are essential for maintaining plant diversity and crop production. Protecting flowering plants, reducing indiscriminate pesticide use and conserving natural vegetation around agricultural fields can help sustain healthy pollinator communities even during periods of climatic stress.

Strengthening Insect Monitoring in India

Although India possesses immense insect diversity, long-term monitoring programmes remain limited for many insect groups. Regular surveys are essential to detect changes in species distribution, seasonal activity and population trends associated with climate variability. National biodiversity monitoring should include forests, agricultural ecosystems, wetlands, grasslands and protected areas. Museum collections maintained by institutions such as the National Pusa Collection (NPC), Zoological Survey of India (ZSI), the ICAR–National Bureau of Agricultural Insect

Resources (NBAIR) and agricultural universities provide valuable historical records that can be compared with present-day observations to understand climate-driven changes in insect distributions. Citizen science initiatives have also become increasingly valuable. Butterfly monitoring programmes, dragonfly surveys, pollinator observation networks and biodiversity documentation through digital platforms have significantly improved our understanding of insect diversity across India. Public participation can complement scientific surveys by generating large-scale biodiversity data from different regions of the country.

Climate-Smart Pest Management

The growing influence of climate variability highlights the need for climate-smart Integrated Pest Management (IPM). Pest management strategies should increasingly incorporate seasonal weather forecasts, climate models and early warning systems. Advances in remote sensing, geographic information systems (GIS), artificial intelligence and ecological modeling now enable researchers to predict favourable conditions for pest outbreaks several weeks in advance. Such forecasting systems can help farmers optimize monitoring schedules, reduce unnecessary pesticide applications and adopt environmentally sustainable pest management practices. Strengthening collaboration among meteorologists, entomologists, ecologists and agricultural extension agencies will improve preparedness for future El Niño events and enhance the resilience of Indian agriculture.

Future Research Priorities

Despite considerable advances in climate science, many questions remain regarding the effects of El Niño on Indian insect biodiversity. Future research should focus on:

- Long-term monitoring of insect populations across different climatic zones.
- Assessing the responses of pollinators, predators, parasitoids and decomposers to changing climate.
- Understanding how changing rainfall patterns influence insect-plant interactions.
- Developing climate-based distribution models for economically important and threatened insect species.
- Integrating taxonomy, molecular tools, ecological modelling and climate science to improve biodiversity assessments.
- Investigating the combined effects of El Niño, habitat fragmentation and land-use change on insect communities.

Addressing these research priorities will help scientists better understand the ecological consequences of climate variability and develop evidence-based conservation strategies.

Conclusion

India's rich insect biodiversity is fundamental to ecosystem functioning, agricultural productivity, and food security through essential services such as pollination, biological control, and nutrient cycling. However, this biodiversity is increasingly vulnerable to climate variability, particularly the effects of El Niño, which alters temperature, rainfall, and monsoon patterns, thereby influencing insect phenology, distribution, abundance, and species interactions. These changes can favour certain pest species while adversely affecting pollinators and natural enemies, leading to disruptions in ecosystem services and ecological balance. As the frequency and intensity of extreme ENSO events are expected to increase under climate change, long-term ecological monitoring, climate-informed

biodiversity conservation and pest forecasting, and interdisciplinary research will be essential for understanding insect responses and developing adaptive management strategies. Strengthening these efforts will be critical to conserving India's insect biodiversity and enhancing the resilience of its natural and agricultural ecosystems.

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