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The Role of Insects in Ecosystems, an in-depth Review of Entomological Research

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ABSTRACT

Insects, integral to Earth's ecosystems, play multifaceted roles that underpin environmental balance and human survival. Spanning roles from pollination to decomposition, these organisms also intersect with socio-economic, cultural, and public health sectors. This review delves into the diverse spheres of insect interactions within ecosystems, from their evolutionary histories to their roles as both predators and prey. The paper sheds light on the intricate predator-prey dynamics, emphasizing insects' roles in pest control and as pivotal food sources for various taxa. The significance of insects in soil ecosystems is elaborated upon, highlighting their contribution to soil health, nutrient cycling, and plant growth. With the looming threats of climate change, habitat destruction, and pollution, insects face unprecedented challenges, which in turn can have cascading effects on ecosystems. In the realm of public health, the review underscores the role of insects as disease vectors, necessitating a balanced approach to ecosystem health and disease management. As vectors, they also catalyze the spread of diseases, creating an intricate balance between maintaining biodiversity and safeguarding human health. The review also touches upon the cultural and economic contributions of insects, from traditional medicine to their utilization in contemporary diets, demonstrating their deep-rooted ties with human societies. With burgeoning technological advancements, the research landscape in entomology is undergoing a seismic shift. Embracing tools such as molecular studies, drones, and AI, the field is poised for groundbreaking insights. As the review suggests, the path forward demands an interdisciplinary approach, amalgamating knowledge from varied scientific domains to grasp the complexities of insect behaviors and interactions fully. In conclusion, insects, though diminutive in size, cast a vast shadow on our planet's functioning. Understanding their roles, challenges, and potential can pave the way for sustainable futures, balancing ecological health with human progress.

Keywords: Entomology; ecosystems; biodiversity; interdisciplinary; conservation.

1. INTRODUCTION

The delicate balance of nature is a testament to the complexity and diversity of life on Earth. Ecosystems, which refer to the interactive tapestry of living organisms and their abiotic environment, underscore a delicate interplay of relationships, dependencies, and synergies. These systems, whether terrestrial or aquatic, tropical or temperate, have developed over millions of years and consist of countless variables that contribute to their stability and productivity. Among the myriad species that contribute to this equilibrium, none are quite as ubiquitous or as influential as insects. With their exceptional diversity and near-global distribution, insects play a critical role in maintaining the health, complexity, and resilience of ecosystems. Ecosystems function as a result of intricate processes, such as nutrient cycling, energy flow, and biotic interactions like predation, herbivory, and mutualism. Each organism, regardless of its size or significance in the food web, plays its part. The butterfly pollinating flowers, the earthworm aerating the soil, the predator hunting its prey—all serve to create a harmonious balance. Disturbances to this balance, either natural like volcanic eruptions, or human-induced like deforestation, can have cascading effects that can be observed at multiple trophic levels. Ecosystem services, such as water purification, air quality regulation, and pollination, are all products of this balance, highlighting the intricate dependence of humans on the health and vitality of these systems [1]. Enter the vast world of insects, a domain representing the epitome of biodiversity. To truly comprehend the magnitude of their diversity, consider this: scientists estimate that there are approximately 10 million different species of insects, accounting for over 90% of all known life forms on Earth [2]. They inhabit nearly every conceivable habitat, from the frozen tundras of the Arctic to the dense rainforests of the Amazon. Insects have evolved to fill almost every ecological niche, adapting to their surroundings in ways that continue to astonish and inspire scientists and naturalists alike. From beetles that can navigate using the Milky Way [3] to ants that farm their own food, the adaptability and innovativeness of insects are unparalleled. Diversity in itself is a marvel, but the geographical distribution of insects amplifies their significance. You'd be hard-pressed to find a location on Earth devoid of insects. They have conquered land, air, and even water. The vast number of species and their wide distribution mean that they have an influence on and are influenced by local conditions and larger global patterns. With climate zones changing due to global factors, the distribution of certain insect species has been observed to shift, reflecting their adaptability but also emphasizing the potential consequences of drastic environmental changes [4].

2. HISTORICAL PERSPECTIVE

Delving into the annals of history reveals a profound and intricate relationship between humans and insects, marked by fascination, wonder, and occasionally fear. The historical perspective on insects is not merely a chronicle of our understanding but also a reflection of our evolving relationship with the natural world. It was during the Renaissance, with its spirit of inquiry and the invention of the microscope, that the study of insects—or entomology—began to resemble a scientific discipline. Pioneering entomologists like Jan Swammerdam in the 17th century embarked on detailed studies of insect anatomy. Swammerdam's meticulous dissections and documentation, especially of the life stages of insects, contradicted the long-held belief in spontaneous generation, showing that insects undergo metamorphosis [5]. This revelation was profound, as it not only deepened understanding of insects but also steered the broader trajectory of biological sciences. Another seminal figure in early entomological studies was Carl Linnaeus, whose binomial nomenclature system in the 18th century brought order to the teeming diversity of life, including insects. His system of classification, though not without its flaws, was instrumental in bringing coherence to the study of insects, facilitating more systematic research and exchanges of knowledge [6]. As scientific methodologies improved and the spirit of exploration surged in the 19th and 20th centuries, entomological studies expanded both in scope and depth. Charles Darwin, during his voyages on the HMS Beagle, made numerous observations on insects, particularly beetles. His notes on their variations, adaptations, and roles in ecosystems contributed to his broader thesis on evolution by natural selection [7]. The growing global movement of goods and people led to an increased awareness of insects as vectors of diseases, culminating in foundational research into mosquitoes and their role in transmitting maladies such as malaria. The 20th century, characterized by technological advancements, witnessed a paradigm shift in entomological studies. The emergence of genetic studies led to groundbreaking research on the fruit fly Drosophila melanogaster, revealing insights into genetics, development, and evolution. This tiny insect, with its short life cycle and easily observable mutations, became a cornerstone in biological research, influencing not just entomology but the broader landscape of genetics and developmental biology.

3. INSECTS AS POLLINATORS

The delicate dance of life on Earth is composed of countless intertwined relationships, with some of the most crucial partnerships formed between flowering plants and the insects that pollinate them. This relationship, driven by the mutual benefits it offers both parties, has not only shaped the evolution of countless species but also profoundly impacts our own existence. At its core, pollination is a reproductive process in plants wherein pollen grains are transferred from the male anther of a flower to the female stigma. This process is the precursor to the formation of seeds, ensuring the continuation of plant species. In the grand tapestry of nature, wind, water, and animals play roles in aiding this transfer, but it's the insects that emerge as the predominant and most efficient pollinators [8]. The role of insects as pollinators can be traced back millions of years, and this evolutionary bond has resulted in various adaptations in both plants and insects. For instance, the vibrant colors, aromatic scents, and intricate patterns on flowers have evolved as beckoning signals for their insect allies. Among the diverse cast of insect pollinators, bees undeniably stand out as the most significant. Their daily quest for nectar and pollen has fashioned them into adept pollinators. As they forage, bees inadvertently ferry pollen between flowers, driven by an insatiable appetite and the need to collect food for their colonies. Notably, some plants have co-evolved with specific bee species, resulting in mutual adaptations that benefit both. The morphology of certain flowers, for example, is so specialized that it aligns perfectly with the body structure of their primary bee pollinators [9]. Beetles, another group of insect pollinators, have a more ancient relationship with plants. Many ancient flowering plants, which evolved before the appearance of bees and butterflies, formed partnerships with beetles. Instead of nectar, these plants often provide beetles with pollen as a food source. The relationship is less specialized than that of bees or butterflies, and as beetles munch on flowers, they inadvertently aid in the transfer of pollen [10]. For humans, the role of insect pollinators in food production is paramount. A study estimates that around 75% of the leading global food crops benefit from animal pollination, with insects being the dominant contributors [11]. Crops such as fruits, vegetables, nuts, and seeds, which constitute essential components of human diets, are particularly reliant on insect pollination. The economic value of this ecosystem service runs into hundreds of billions annually, underscoring the economic dependency of agriculture on these tiny pollinators.

3. INSECTS AS DECOMPOSERS

The natural world operates in cycles, and one of the most crucial facets of this cyclical existence is the decomposition of organic matter. While decomposition might be perceived as nature's way of cleaning up, it's fundamentally a process of transformation – turning the old into the raw materials for the new. In this grand cycle, insects play an indispensable role, ensuring that death and decay give way to life anew. Decomposition is the process where organic substances are broken down into simpler organic or inorganic matter. This breakdown is achieved through two primary mechanisms: physical decomposition, where organic materials are mechanically disassembled, and chemical decomposition, where organic substances undergo chemical reactions, typically aided by enzymes, to transform into simpler compounds. Insects excel in both mechanisms, often introducing organic material to microbes that further aid the decomposition process. One cannot discuss decomposition without highlighting the invaluable role of beetles, particularly the carrion beetles and the dung beetles. Carrion beetles are nature's undertakers. They are attracted to the carcasses of dead animals, where they not only feed on the decomposing flesh but also lay their eggs. As their larvae hatch and grow, they continue the process of breaking down the carcass, converting what was once a living creature into simpler organic compounds [12]. Dung beetles, on the other hand, specialize in another kind of decomposition. These beetles consume feces, aiding in breaking down complex organic materials present in dung, which often contains undigested plant material. By burying and consuming dung, these beetles play a role in recycling nutrients and organic matter back into the soil. Termites, often perceived as pests for their wood-eating habits, are undeniably master decomposers. These insects feed on cellulose, the primary component of plant cell walls. With the help of microbes in their gut, termites can break down cellulose, converting wood, dead leaves, and other plant materials into simpler compounds [13]. By doing so, they transform dead plant matter, which would otherwise accumulate, into organic compounds that can be utilized by other organisms.

4. INSECTS AS PREDATORS AND PREY

The intricate web of life is replete with multifaceted relationships, and among the most riveting are those of predators and their prey. Within the vast realm of the insect world, these dynamics play out on a microscopic scale, yet their implications resonate through ecosystems, shaping biodiversity, controlling populations, and dictating the evolutionary trajectory of countless species. Insects, due to their immense diversity and abundance, find themselves both as hunters and the hunted. This dual role underscores their significance in maintaining ecological balance. Predator insects, such as mantises, ladybugs, and dragonflies, employ a variety of strategies to capture and consume their prey. These predators are evolutionarily equipped with specialized appendages, keen sensory organs, and often, stealthy behaviors, all fine-tuned for the hunt. For instance, the praying mantis, with its raptorial forelegs and an ability to swivel its head almost 180 degrees, is a formidable predator, consuming anything from insects to small vertebrates [14]. The ladybug, often symbolized for its benign appearance, is a voracious predator of aphids, safeguarding plants from potential pest damage. The role of predatory insects in controlling pest populations is invaluable, especially in the context of agriculture. Pest insects, which can decimate crops and result in significant yield losses, are naturally kept in check by their insect predators. Biological control, an approach that harnesses the predator-prey dynamics of insects, is employed to manage pest populations without resorting to chemical pesticides. By introducing or encouraging the proliferation of natural predators, pest populations can be reduced, ensuring crop health. For instance, the release of ladybugs in fields and gardens to combat aphid infestations has been a widely recognized practice in sustainable agriculture [15].

5. INSECTS IN SOIL ECOSYSTEMS

From the sweeping forests to the vast grasslands, beneath our feet lies a world teeming with life, both intricate and profound. This subterranean realm, the soil, is the very foundation of terrestrial ecosystems. And in the diverse tapestry of life that thrives within it, insects play a role that is pivotal, complex, and yet often understated. Their activities influence the soil's physical structure, its biological networks, and its interactions with the world above - the plants. Let's begin with one of the most tangible impacts of insects on the soil: aeration and turnover. The simple act of burrowing and tunneling by numerous insects facilitates the movement of air and water through the soil. Earthworms, though not insects, are often the most celebrated of soil engineers. Insects such as beetles, ants, and termites engage in similar behaviors with equally profound impacts. Dung beetles, for instance, burrow into the soil to bury feces, which serves as both food and a nesting place. This activity not only aids in nutrient recycling but also in improving soil structure by creating channels that enhance water infiltration and reduce erosion [16]. Ants, with their intricate underground colonies, are another group of master soil engineers. Their subterranean chambers and tunnels can stretch extensively, significantly impacting soil structure. The act of tunneling and transporting soil particles from deeper layers to the surface, a behavior particularly prominent in ant species, aids in mixing the soil – a process analogous to natural tilling. This constant movement and redistribution of soil particles promote aeration, ensuring that even the deeper soil layers receive adequate oxygen, essential for microbial activity and root respiration. Termites, especially the subterranean species, engage in behaviors that shape the soil ecosystem. Feeding on dead plant material, they break down complex organic compounds, transforming them into simpler substances. But beyond their role as decomposers, their nesting and foraging activities, similar to ants, lead to soil turnover. They transport soil particles, mix them with organic matter, and in doing so, influence both the soil's physical structure and its chemistry.

6. INSECTS AS DISEASE VECTORS

Across the broad expanse of life on Earth, the influence of insects stands paramount, not just in their sheer numbers, but in their profound interactions with other living organisms. While their roles in pollination, decomposition, and as members of the food web are well celebrated, it is equally essential to understand and acknowledge their capacity as vectors of diseases. This capability, not merely a biological mechanism, has broader implications for public health, ecology, and the balance we seek to maintain in ecosystems. Disease vectors are organisms that transmit infectious agents from one host to another. While various organisms can serve this role, insects have historically been the most impactful vectors for humans and other animals. Their capacity to harbor and spread infectious agents arises from their close interactions with hosts and their adaptability to various environments. This adaptability ensures that they often thrive even in changing ecosystems and human-modified landscapes. In the annals of human history, few insects have left as indelible a mark as mosquitoes. Mosquitoes, particularly species of the genera Anopheles, Aedes, and Culex, are responsible for transmitting a host of diseases. Malaria, a disease caused by the Plasmodium parasite, is transmitted to humans through the bite of infected female Anopheles mosquitoes. With hundreds of millions of cases reported annually, malaria remains a significant public health concern, especially in parts of Africa, Asia, and South America [17]. Beyond malaria, mosquitoes play a role in transmitting other infectious diseases, including dengue, Zika, and West Nile virus, each having its own set of health, social, and economic implications. Ticks, while technically arachnids and not insects, are another significant group of disease vectors. These ectoparasites, by feeding on the blood of their hosts, can transmit a suite of pathogens. Lyme disease, a growing concern especially in North America and parts of Europe, is caused by bacteria transmitted to humans through the bite of infected black-legged ticks. Additionally, ticks are vectors for other diseases like Rocky Mountain spotted fever and tick-borne encephalitis, which impact both human and animal health.

7. IMPACT OF ENVIRONMENTAL CHANGES ON INSECTS

In the grand theater of life on Earth, insects occupy roles so numerous and varied that their significance cannot be overstated. These tiny, multitudinous beings impact every corner of our biosphere, from the deepest forests to the urban sprawl of our cities. But in the shadow of the Anthropocene, a new epoch marked by profound human influence, these insects are navigating a world rapidly changing. The overarching narrative of environmental changes, be it through climate shifts, habitat alterations, or direct anthropogenic pressures like pollution, holds immense sway over the fate of insect populations worldwide. Let us first turn our gaze to the omnipresent issue of our time: climate change.

With the steady rise in global temperatures, driven by human activities and the greenhouse effect, the ecosystems and habitats insects inhabit are undergoing vast changes. Many insect species, being ectothermic, rely heavily on external environmental temperatures to regulate their metabolic processes. As a result, even slight shifts in temperature can influence their life cycle events, such as breeding, hatching, and migration. For example, studies have shown that certain butterfly species are now emerging earlier in the spring than they did a few decades ago, a clear response to warming temperatures [18]. But such changes are not without consequences. If insects and the plants or animals they interact with respond differently to climate change, it can result in a mismatch. Such mismatches can be detrimental, for instance, if pollinators emerge at a time when their host plants haven't flowered yet.

8. CONSERVATION OF INSECT DIVERSITY

In the vast kaleidoscope of life on Earth, insects represent the majority of biodiversity, showcasing an incredible array of forms, functions, and ecological roles. Their sheer numbers and variety are unparalleled in the animal kingdom, making them a critical component of our planet's ecosystems. From decomposers that recycle organic matter to pollinators vital for flowering plant reproduction, insects are central to maintaining the balance of nature. But as with many components of our world's biodiversity, insects too are under threat. Recognizing these threats and understanding the importance of conserving insect diversity are essential endeavors for our time. The significance of conserving insect biodiversity cannot be overstated. Insects, given their myriad roles, serve as the backbone of many ecosystems. Their interactions with plants, other animals, and the environment ensure the continued functioning of these ecosystems. For instance, pollinators like bees, butterflies, and beetles enable the reproduction of a staggering number of plant species, including those that constitute a significant portion of human food sources. Without these diligent pollinators, our landscapes and diets would be drastically different. Similarly, insect decomposers play a pivotal role in breaking down dead organic material, cycling nutrients back into the soil, and providing a foundation for plant growth. As prey for numerous animals such as birds, reptiles, and amphibians, insects occupy a fundamental position in the food web. Their decline could precipitate a cascade of negative effects, impacting predators and the ecosystems they inhabit [19].

9. CULTURAL AND ECONOMIC ROLES OF INSECTS

When contemplating the significance of insects to our lives, the instinctive reactions might often revolve around their ecological roles: pollinators, decomposers, predators, and even vectors of disease. An exploration into human history, cultural practices, and economic systems reveals a nuanced relationship. Insects have, for millennia, played pivotal roles in traditional medicines, diets, religious rituals, art, and commerce. The intertwining relationship between humans and insects expands beyond ecology, delving deep into the realms of culture and economy. Tracing back to ancient civilizations, insects have been consistently integrated into human diets. Entomophagy, or the consumption of insects, has been a dietary practice in various cultures worldwide, from Africa to Asia, and even in some parts of the Americas. Rich in proteins, essential fats, vitamins, and minerals, insects present a nutritious source of food [20]. For instance, the larvae of palm weevils, popular in parts of Africa and Asia, not only provide proteins but also essential amino acids and micronutrients. Similarly, silkworm larvae, crickets, grasshoppers, and ants are consumed in various preparations, whether roasted, boiled, or integrated into traditional dishes. Beyond the immediate nutritional value, insects play a significant role in traditional medicines. For instance, in Traditional Chinese Medicine, certain insects are considered to possess therapeutic properties, beneficial for various ailments. Ground cicada slough is believed to have cooling properties, providing relief for fevers or eye issues. Similarly, the blister beetle, when utilized under precise conditions, is thought to possess aphrodisiac qualities, a concept echoed in several cultures beyond China [21]. The intricate relationship between humans and insects isn't limited to diet and medicine; it spills into the realm of commerce and trade.

10. FUTURE RESEARCH DIRECTIONS

Entomology, the scientific study of insects, has witnessed significant advancements over the past few centuries. The exploration began with rudimentary observations, where insects were studied for their visible behaviors and anatomy.

With the advent of modern technology and the surge in interdisciplinary research endeavors, the study of insects is not merely confined to understanding their physiology or behavior. It now stretches its tendrils into molecular studies, the world of artificial intelligence, and even the use of drones, opening a plethora of avenues for future research directions. Historically, the magnifying lens and the observational prowess of researchers were the primary tools in entomological studies. Today, there's a shift towards understanding the intricate genetic makeup of insects. Molecular studies promise a deeper understanding of insect biology, behavior, and evolution. For instance, by analyzing the genetic codes of insects, researchers can gain insights into their adaptive mechanisms, their resistance to pesticides, or their evolution in response to changing environments [22]. These genetic explorations can be pivotal in devising strategies for pest control, especially at a time when many traditional pesticides are becoming less effective due to increasing resistance. The evolving landscape of technology has also brought forth the potential of drones in entomological studies. Drones, or unmanned aerial vehicles (UAVs), offer a bird's eye view of habitats, enabling researchers to monitor vast areas efficiently. This is especially crucial in understanding migratory patterns, habitat

Table 1. Estimated numbers of described species across the largest orders of insects (>1,000 species), as of 2019a [24]

Order	Common name	Feeding habit	Numbers of described species
Blattodea∗,b	Cockroaches/termites	Detritivores	5,710
Coleoptera	Beetles	Various	392,415
Dermaptera	Earwigs	Detritivores	1,982
Diptera	True flies	Various	160,591
Ephemeroptera	Mayflies	Aquatic predators	3,281
Hemiptera	Bugs	Herbivores/predators	104,165
Hymenoptera	Bees, ants, wasps	Predators/herbivores	152,677
Lepidoptera	Butterflies, moths	Herbivores	158,570
Mantodea∗	Mantises	Predators	2,447
Neuroptera	Net-winged insects	Predators	5,937
Odonata	Dragonflies, damselflies	(Aquatic) predators	6,650
Orthoptera	Grasshoppers, crickets	Herbivores	24,481
Phasmida∗	Stick insects	Herbivores	3,270
Plecoptera	Stoneflies	Aquatic herbivores	3,930
Psocodea	Booklice, true lice	Parasites/detritivores	10,746
Siphonaptera	Fleas	Parasites	2,086
Thysanoptera	Thrips	Herbivores	6,157
Trichoptera	Caddisflies	Aquatic predators	15,233

Table 2. Some examples of ecosystem services provided by insectsa [25]

Order	Ecosystem service	Feeding guild	Examples
Hymenoptera	Biological control	Predators	Formicidae (ants), Vespidae (wasps)
Hymenoptera	Biological control	Parasitoids	Ichnemonidae, Braconidae, Chalcidoidea
Hymenoptera	Pollination	Herbivores	Mostly Apidae (bees)
Hymenoptera	Seed dispersal	Scavengers	Formicidae (ants)
Hymenoptera	Bioturbation	Scavengers	Formicidae (ants)
Coleoptera	Biological control	Predators	Carabidae (ground beetles), Coccinellidae (ladybugs)
Lepidoptera	Pollination	Herbivores	Moths, mostly nocturnal
Diptera	Animal decomposition	Scavengers	Many families
Blattodea	Plant decomposition	Decomposers	Termites, dung beetles, weevils
Many	Human food	Many	Termites, locusts, beetle larvae
Blattodea	Bioturbation	Decomposers	Termite constructions

Table 3. Roles of Various Insect Orders in Soil Ecosystems [26]

Order	Role in Soil Ecosystem	Feeding Guild	Examples
Hymenoptera	Soil Aeration	Scavengers	Formicidae (ants)
Coleoptera	Nutrient Cycling	Detritivores	Scarabaeidae (dung beetles)
Isoptera	Decomposition	Decomposers	Termites
Diptera	Organic Matter Decomposition	Scavengers	Various families of flies
Orthoptera	Soil Tilling	Herbivores	Crickets, mole crickets
Lepidoptera	Organic Matter Incorporation	Herbivores	Various species of soil-dwelling larvae
Thysanoptera	Fungal Decomposition	Fungivores	Various families of thrips
Hymenoptera	Soil Fertility	Predators	Sphecidae (digger wasps)
Collembola	Soil Structure	Detritivores	Springtails
Chilopoda	Predator Role	Predators	Centipedes
Diplopoda	Organic Matter Decomposition	Detritivores	Millipedes

Table 4. Insect Orders as Vectors of Human and Animal Diseases [27]

Order	Disease	Feeding Guild	Examples
Diptera	Malaria	Blood-feeding	Anopheles mosquitoes
Diptera	Dengue Fever	Blood-feeding	Aedes mosquitoes
Diptera	West Nile Virus	Blood-feeding	Culex mosquitoes
Diptera	Sleeping Sickness	Blood-feeding	Tsetse flies
Siphonaptera	Plague	Blood-feeding	Fleas
Hemiptera	Chagas Disease	Blood-feeding	Kissing bugs (Triatominae)
Hemiptera	Typhus	Blood-feeding	Lice
Phthiraptera	Louse-borne diseases	Blood-feeding	Human lice
Diptera	Yellow Fever	Blood-feeding	Aedes mosquitoes
Diptera	Leishmaniasis	Blood-feeding	Sandflies

preferences, or even the spread of certain insect-borne diseases. A study in the African savannahs, for instance, can utilize drones to monitor the movement and population density of locust swarms, which are notorious for their devastating impacts on agriculture [23].

11. CONCLUSION

Insects, undeniably diverse and intricately linked with the planet's ecosystems, serve pivotal roles, from pollinators and decomposers to disease vectors. Their significance transcends mere ecological contributions, extending to cultural, economic, and scientific domains. As technology propels entomological research into novel territories, integrating molecular studies, drones, and AI, an interdisciplinary approach emerges as crucial. By transcending traditional academic boundaries, we gain a holistic perspective on insect behaviors, interactions, and impacts. Embracing these future research avenues will not only deepen our understanding of these remarkable creatures but also bolster our efforts in conservation, public health, and sustainable coexistence. The future of insect studies, undoubtedly, promises profound insights and transformative implications.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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