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Review

Insects' contributions to people: ecosystem services and functions provided by insects

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With an estimated 10 million species, insects are central to nearly every terrestrial and freshwater ecosystem, driving ecological processes that support core ecosystem functions and the services derived from them. We review the contributions insects make to people, with a focus on supporting, regulating, and provisioning ecosystem services, rather than the ways these services impact human quality of life (e.g. livelihood creation, public health). We use the confidence framework adopted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to assess the amount and quality of scientific evidence, as well as the level of agreement within the scientific community. Insects are critical for habitat formation and maintenance through their roles as decomposers of plant and animal matter, removing dead biomass and cycling nutrients through ecosystems. As seed dispersers and pollinators, they structure plant communities, influence the genetic diversity of wild plants and crops, and are essential for food security. They play roles in decontaminating soils, purifying freshwater, regulating climate cycles, and transporting nutrients. In trophic webs, they regulate pest and disease vector populations,

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and serve as prey for insectivorous species that directly and indirectly support food security and livelihoods. Products derived from insects span from fabrics and dyes, to wound dressing, to water-repellant materials, and compounds used in vaccines. Declines in insects jeopardize ecosystem functions and human well-being in ways that far exceed economic accounting, eroding life-supporting services whose value is beyond measure.

Keywords: ecosystem service, ecosystem function, functional diversity, insect conservation, nature's contributions to people

Introduction

Insects are fundamental to all life (Wilson 1987). With an estimated 10 million species or more (Colwell et al. 2026), the sheer ubiquity and diversity of insects highlight their importance. While the role of insects as pollinators has received substantial global attention (Potts et al. 2016), insects are far more diverse and fill far more functional roles than pollination alone. Insects are central to ecological processes, global energy cycles, and provision of materials and services that support human societies and the other organisms with which we share the planet (Noriega et al. 2018, Noriega and Schowalter 2024). Insects are the glue that holds together terrestrial and aquatic ecosystems and play key roles in habitat creation through ecosystem engineering and formation of structures such as termite mounds that other organisms rely on (Fig. 1) and habitat maintenance including dead biomass removal and decontamination (Beare et al. 1995, Barton et al. 2013, Schowalter 2013). They regulate the population dynamics of other organisms via their roles as seed dispersers (Giladi 2006, Penn and Crist 2018), pollinators (Ollerton et al. 2011), and as food for insectivores (Grames et al. 2023). With declines in insects, terrestrial and freshwater ecosystems and food webs will be destabilized. Plants will likely have limited seed production and dispersal and lose genetic diversity (Barrett and Harder 2017, Artamendi et al. 2025), and many vertebrate species (Cooke et al. 2026) that consume insects could be negatively impacted. Global carbon cycles could be altered, as insects regulate forest pests, are key disturbance agents, and decompose organic matter (Lavelle et al. 1997, Yang 2006, Zeng et al. 2024). Nutrient fluxes from aquatic to terrestrial habitats are largely driven by mass insect emergences (Gratton et al. 2008), and the effects of this loss of carbon and nitrogen cycling could have cascading impacts on plant community dynamics, riparian habitats, and the organisms that rely on these nutrients (Fig. 2). Declines in insect abundance and biomass at estimated rates of 1% to 2% per year (Wagner et al. 2021) could have devastating consequences for biodiversity and ecosystem function as we lose these fundamental services they provide.

The essential roles insects play in ecosystem function sustain a vast range of biodiversity, and indirectly are also vital

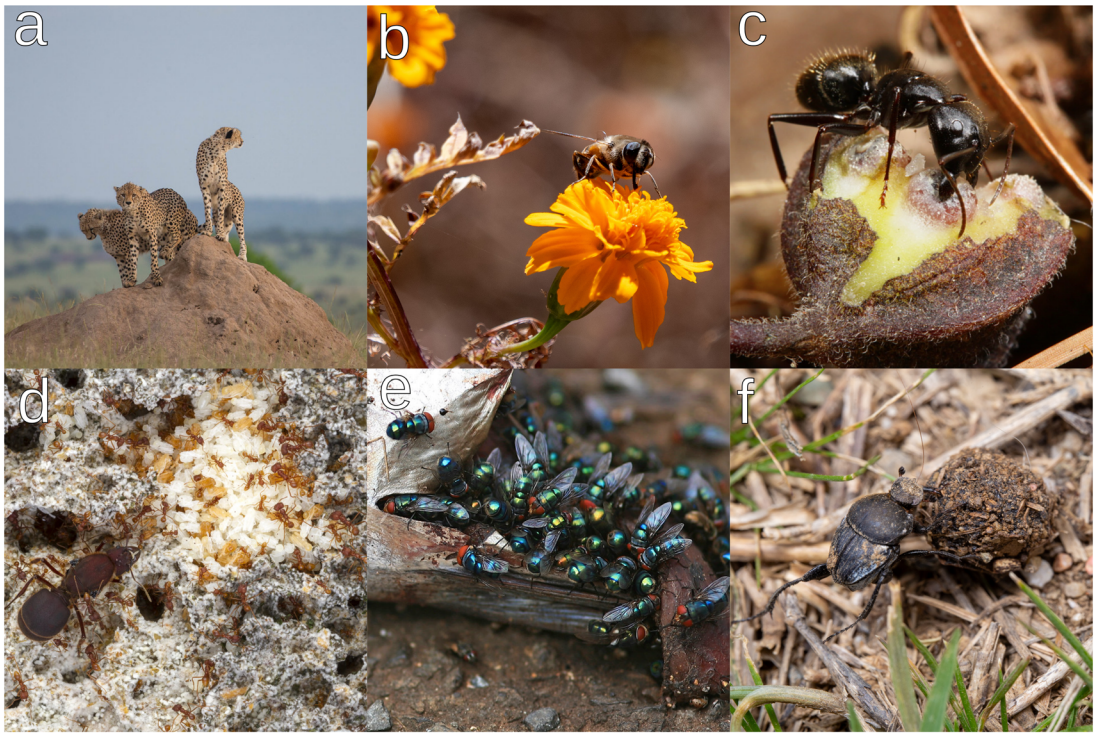


Fig. 1. Supporting ecosystem services by insects include creating and maintaining habitat for other organisms through their roles as (A) ecosystem engineers such as the creation of termite mounds that many vertebrate species use for habitat, (B) pollinators of wildflowers and agricultural crops, (C) seed dispersers, especially for myrmecochorous plants (Patrick Coin), and (D) through soil formation and decontamination such as nutrient deposition by ant colonies. They also maintain habitats through decomposition and removal of dead biomass such as (E) necrophagous species eating carcasses (Laszlo Ilyes) and (F) coprophagous species removing dung from the environment. Photos are public domain or issued under Creative Commons licenses by named individuals.

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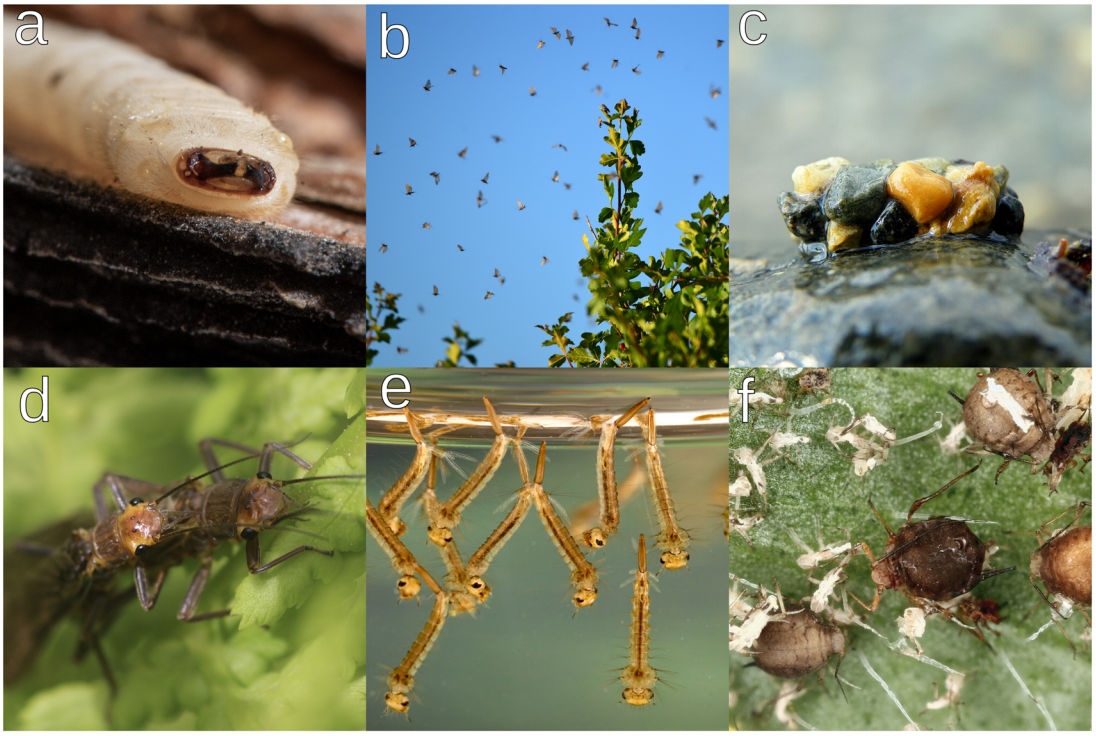


Fig. 2. Regulating services provided by insects. Insects (A) regulate climate through decomposition of deadwood such as by saproxylic beetles and termites, (B) transfer nutrients across ecosystem boundaries through mass emergences of aquatic insects (Tom Koerner), and (C) contribute to stream sediment stability such as caddisfly larvae connecting substrates with silk, and also to terrestrial soil stability by burrowing such as termites (Marija Gajic). They serve as (D) bioindicators of water quality while in their larval stages, and as natural enemies they regulate populations of organisms detrimental to humans such as (E) disease vectors (James Gathany) and (F) crop pests. Photos are public domain or issued under Creative Commons licenses by named individuals.

contributions to humanity that we stand to lose if they decline further (Fig. 3). Aquatic insects regulate freshwater quality through water purification and serve as bioindicators of water contamination (Suter and Cormier 2015), supporting the world's supply of drinking water. As pollinators and seed dispersers, insects are essential to ensuring the global food supply through crop pollination and maintenance of crop genetic diversity (Artamendi et al. 2025). Predatory and parasitoid insects regulate crop pests, keeping their populations in check and supporting high crop yields (Karp et al. 2018). While some insects are important disease vectors, others mitigate disease transmission, reducing the spread of vector-borne diseases like malaria by consuming early life stages of disease vectors (Shaalan and Canyon 2009, Staats et al. 2016). They provide humanity with food indirectly through their contributions to food security and by serving as feed for livestock and for many species of vertebrates that are hunted or fished for subsistence (Anyasi et al. 2025). Directly they contribute to food security through entomophagy which is practiced throughout much of the world (Omuse et al. 2024), and to energy security in the form of insect-based biofuels (Mohan et al. 2026). The contributions of insects to the engineering and medical world are vast, and there is huge untapped potential in insect biodiversity to revolutionize medical approaches from drug delivery (e.g. chitosan), to understanding the genetic underpinnings of diseases (e.g. through research on the fruit fly *Drosophila melanogaster* Meigen 1830), and producing compounds with anticancer properties (Siddiqui et al. 2023). The contributions of insects to people are as diverse as insects themselves, and it is imperative that conservation actions are taken to mitigate insect biodiversity loss and preserve their contributions to people.

Here, we review the many contributions insects make to people and the ecosystem services they provide (Fig. 4), from supporting services (e.g. habitat creation, pollination), to regulating services (e.g. climate regulation, nutrient and energy cycling, regulation of detrimental organisms like pests and disease vectors), and provisioning services (e.g. insects as food and feed, biofuel energy production, and materials and resources used in medicine). The ecosystem services provided by insects are not only critical for ecosystem function and support nearly all freshwater and terrestrial organisms, they also have enormous economic value, and are essential to human well-being and survival. Many of the contributions insects make to people, such as pollination, contribute to fundamental ecosystem function and are also valued for improving human quality of life through food security. In this review, we focus solely on insects' contributions to people in the sense of the IPBES Nature's Contributions to People, which places greater emphasis on ecocentric values, rather than the cascading impacts that insects have on human quality of life (Fig. 5) which places greater emphasis on anthropocentric values and is treated in detail by Ware et al. (2026).

Throughout this review, we adopt the framework used by the IPBES for assessing the level of evidence and scientific consensus supporting each key takeaway about the contributions of insects to people (Fig. 4). In this framework (Brondizio et al. 2019), key takeaways can be supported by a large amount of

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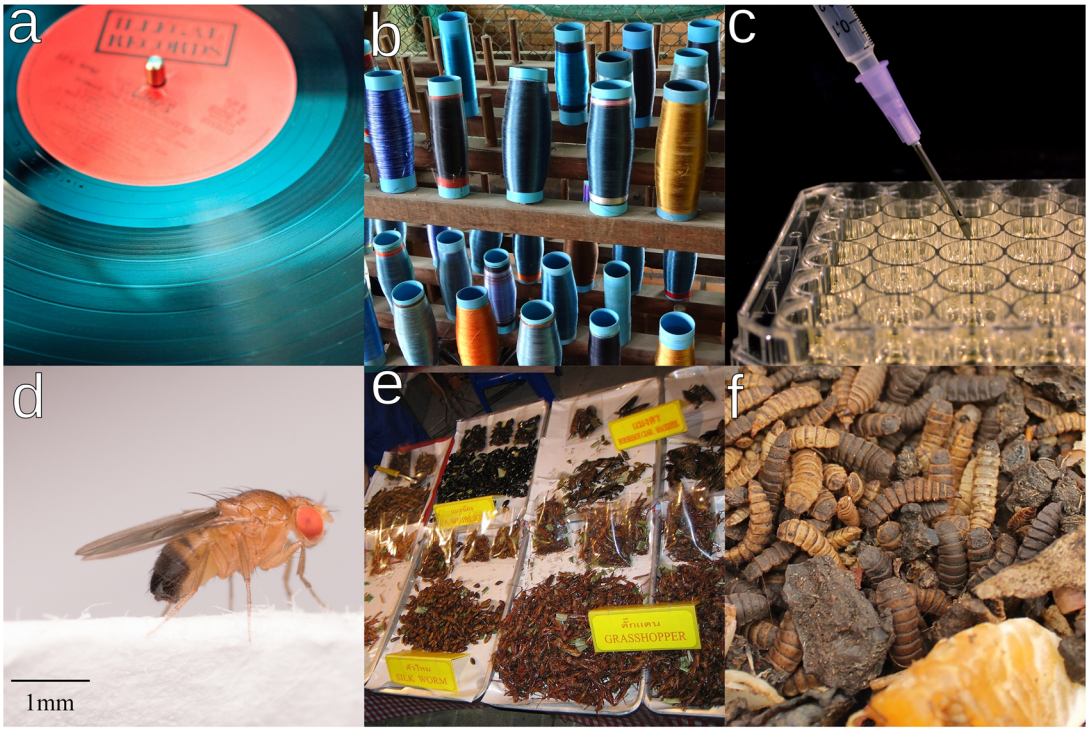


Fig. 3. Insects provide us with materials that have been, or have historically been used, produce (A) vinyl records and other products created from shellac such as varnishes, (B) silk and textiles, as well as dyes such as carmine and vermillion (Adam Jones), and (C) medically important products like chitosan, derived from insect exoskeletons and used for drug delivery and wound dressing (Adam Taylor). They are also used (D) as model organisms underpinning genetic discoveries such as *Drosophila melanogaster*, (E) as food for humans and the backbone of edible-insect economies as well as as feed for livestock and animals hunted for subsistence (Chad Forbz), and (F) in insect-based biofuel production and waste management such as use of black soldier fly larvae to decompose waste and convert it to animal feed or biofuel (Rodrick Rajive Lal). Photos are public domain or issued under Creative Commons licenses by named individuals.

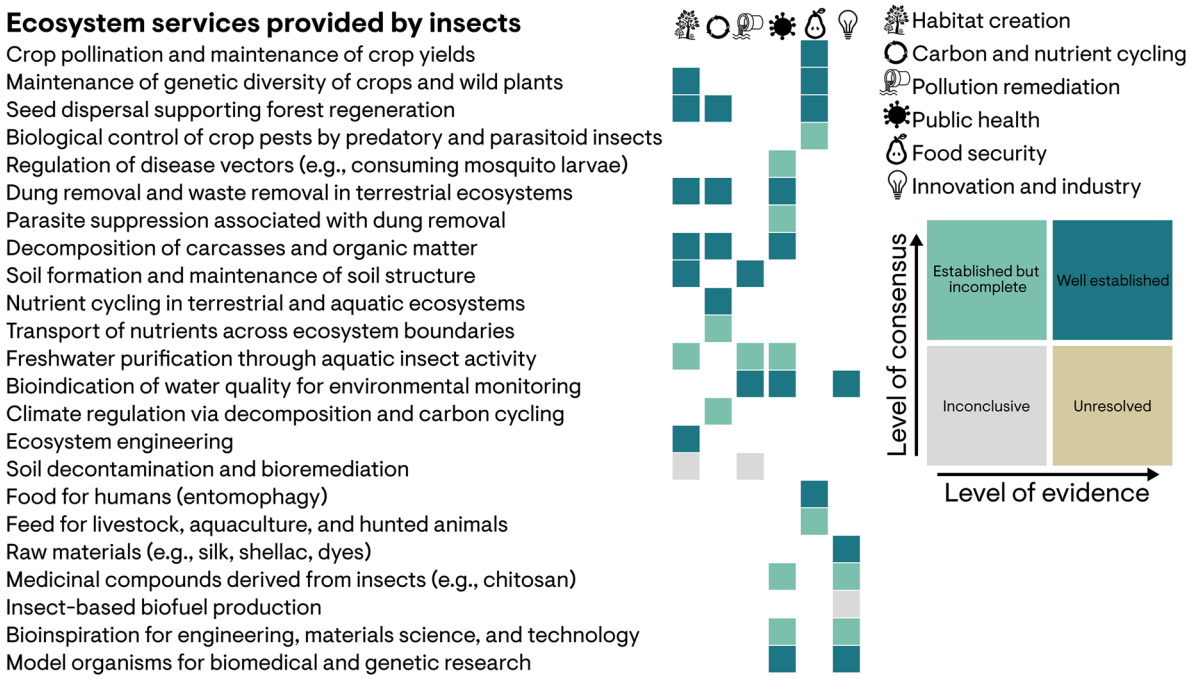


Fig. 4. Several of the many ecosystem services provided by insects, grouped according to their primary contributions to people being either through habitat creation for other organisms, global carbon and nutrient cycling, pollution remediation and mitigation, public health and disease transmission reduction, global food security, or research innovation and industrial advancements. Contributions are colored according to the level of confidence in the evidence, depending on if they are well established (teal), established but incomplete (mint), unresolved (yellow), or inconclusive (gray).

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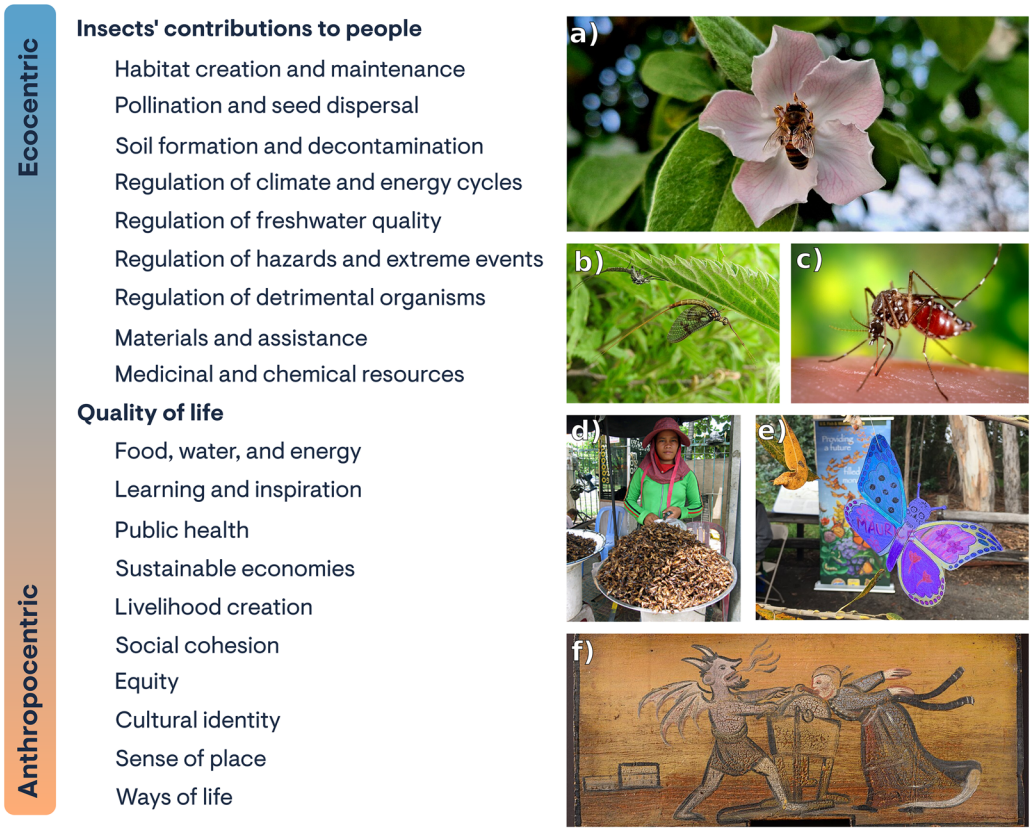


Fig. 5. Insects provide many ecosystem services, valued for their ecocentric contributions to people, that in turn support human quality of life, characterized by a more anthropocentric value system. For instance, (A) insects pollinate many wild plants and also agricultural crops like quince, (B) aquatic insect emergence represents a massive flux of energy among ecosystems that is important for ecosystem function, and also regulate (C) disease vectors by consuming mosquito larvae, contributing to human quality of life by supporting public health. Insects like termites and grasshoppers are essential for habitat creation, soil formation, and nutrient cycling, and (D) are also frequently consumed and support human livelihoods. Bees and butterflies serve as pollinators, and also inspire cultural identity and a sense of place such as (E) in celebrations of Dia de Los Muertos and (F) illustrations that adorn honey bee hives in Europe.

evidence with high agreement among studies (well established), by a large amount of evidence with conflicting or contradictory results that may be highly context dependent (unresolved), by minimal evidence that is highly aligned or agreed upon by most experts but where key questions are unaddressed (established but incomplete), or may be an emerging idea that has minimal evidence and low scientific consensus (inconclusive). The latter categories, established but incomplete and inconclusive, do not necessarily indicate that an idea does not have merit or is not likely to be true, but rather that there is not sufficient evidence in the scientific literature at this time to reach broad consensus. These topics merit further investigation, funding, and attention from the scientific community, yet the lack of evidence should also not hamper conservation activities or policies that address these issues (Forister et al. 2019). If insects continue to decline, humanity stands to lose the many ecosystem services and contributions that insects make to people, with potentially disastrous consequences for ecosystem function, habitat stability, food security, green energy, and public health.

Habitat Creation and Maintenance

Many species rely on insect-built structures for habitat (well established). Due to their ubiquity, diversity, and often specialized functional roles, insects are among the most influential ecosystem engineers on earth (Lavelle et al. 1997, Jouquet et al. 2006, Hölker et al. 2015). Termites and ants, in particular, are keystone taxa in many ecosystems (Fig. 1A). Termites construct extensive subterranean and aboveground mounds that regulate microclimate, providing refugia and nesting sites for numerous vertebrates (Lobry de Bruyn and Conacher 1990, Pennisi 2015, Cooke et al. 2026). Bioturbation by termites also maintains earthen mounds, particularly in arid environments, which serve as key grazing and burrowing sites for mammals and the structure of which alters plant community composition (Sileshi et al. 2010). Ant nests are often used by other species due to their stable humidity and effects on soil structure and function (Fig. 1D; Folgarait 1998, Farji-Brener and Werenkraut 2017), especially in nests constructed by fungus-growing ant species that are frequently used as oviposition sites by herpetofauna (Cooke et al. 2026). Wood-boring species also accelerate decomposition and create microhabitats in wood used by invertebrates, fungi, and other taxa (Stokland et al. 2012, Ulyshen 2016).

Plant community assembly patterns are often driven by insect activity (established but incomplete). When termites construct mounds, they aerate soil, enhance water filtration, and concentrate nutrients, creating fertile "islands" that influence vegetation patterns (Holt and Lepage 2000, Jouquet et al. 2006, Sileshi et al. 2010, Pennisi 2015). Ants likewise modify landscapes through their nest building, foraging, and seed dispersal activities. They transport and mix soil (Eldridge and

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Pickard 1993, Richards 2009), redistributing nutrients across the landscape (Farji-Brener and Werenkraut 2017) and subsequently impacting plant communities. Moreover, many insects play key roles in nutrient cycling, soil formation, and seed dispersal, which maintain ecosystem function and structure plant community assembly dynamics (Prior et al. 2020). For instance, ant-plant mutualisms can determine plant demography and vegetation structure (Rosumek et al. 2009, Kamaru et al. 2024), and dung beetles improve soil structure (Nichols et al. 2008, Slade et al. 2016) providing key soil resources for plant communities.

Insects facilitate natural forest regeneration through seed dispersal and pollination (established but incomplete). Global forest conservation efforts depend on insects, which provide critical seed dispersal (Fig. 1C) and pollination (Fig. 1B) services. Indeed, the most threatened processes for forest regeneration are plant-animal interactions, the vast majority of which are plant-insect interactions (Neuschulz et al. 2016). Over half the plants in tropical ecosystems are dispersed by animals, with vertebrates serving as the primary dispersers and insects as secondary dispersers of seeds that have passed through vertebrate guts (Levey and Byrne 1993, Crespo-Perez et al. 2020). While vertebrates disperse seeds over longer distances, they often deposit seeds in unsuitable habitat; insects will redisperse seeds into suitable microsites where they are more likely to successfully germinate and develop (Levey and Byrne 1993, Vander Wall et al. 2005). In their role as secondary dispersers, insects facilitate regeneration of degraded habitats, including where vertebrates are lost or in decline (Anjos et al. 2020). They also serve as pollinators for over 75% of tree species in tropical forests (Howe and Smallwood 1982) and 30% to 40% of trees in temperate forests (Jordano 2000). These two services provided by insects, seed dispersal and pollination, are far more important than any other factors—seed predation, recruitment, and herbivory—in driving forest regeneration (Neuschulz et al. 2016).

Dung removal by insects is a critical ecosystem service that is sensitive to anthropogenic disturbance (well established). Animal feces are removed from the soil surface via a combination of microbial processes, burial by insects, and consumption by insects (Fig. 1F). Dung removal is tightly linked to many other ecosystem services, such as parasite suppression by reducing habitat and nutrient availability for parasites transmitted via feces, secondary seed dispersal for seeds deposited in animal feces, stimulating plant productivity by dispersing nutrients, and mitigating methane emissions (Nichols et al. 2008). Across most terrestrial ecosystems, dung beetles (Coleoptera: Scarabaeoidea) are chiefly responsible for dung removal. Most dung beetle species are obligate coprophages (Hanski and Cambefort 1991) and exhibit a wide variety of physical and life history traits that underpin their importance in dung removal. Feeding guild is an important predictor of dung removal contributions, and species that build subterranean nests where broods develop within translocated dung (i.e. rollers and tunnellers) generally contribute more to this ecosystem service than species that feed and brood within the dung itself (i.e. dwellers) because of the processing and movement of dung (Buse and Entling 2020). Larger bodied species also contribute more to dung removal than smaller species. Because species' traits are associated with different levels of dung removal (DeCastro-Arrazola et al. 2020), changes in community composition—including the loss of functionally efficient species or declines in their abundance—can result in rapid shifts in this ecosystem service (Nervo et al. 2014, Manning and Cutler 2018, Milotić et al. 2019). Human activity, primarily land use change and the use of veterinary parasiticides, are well established as drivers of dung beetle community composition and abundance (Noriega et al. 2021), and as such dung removal is an ecosystem service that is highly sensitive to anthropogenic disturbance.

Carcass decomposition by insects is critical for dead biomass removal and nutrient cycling in terrestrial and aquatic ecosystems (well established). Carrion, the decaying flesh of a deceased animal, is a relatively small part of the detritus pool (Parmenter and MacMahon 2009), yet is disproportionately important for ecosystem function and nutrient cycling relative to more common forms of detritus like decaying plant matter (Barton et al. 2013). Large vertebrate carcasses in particular can dramatically alter soil nitrogen levels in localized patches (Parmenter and MacMahon 2009) affecting nutrient availability which in turn impacts bacteria and fungi (Bump et al. 2009a) and plant communities (Towne 2000, Bump et al. 2009b). Given the importance of carrion decomposition to ecosystem function and structure, the role of insects in decomposition is critical to both removing dead biomass from terrestrial ecosystems and facilitating nutrient cycling (Fig. 1E). The majority of insects responsible for carcass decomposition belong to Diptera and Coleoptera, which represent 60% of insect fauna on carrion (Moretti et al. 2008), yet because carrion is extremely nutrient-rich, it attracts a wide array of insects (Braack 1987, Watson 2004). These insects include necrophagous species that feed on carcass tissue such as blow flies (Diptera: Calliphoridae) and flesh flies (Diptera: Sarcophagidae). Unlike carrion flies, which are typically necrophagous, carrion beetles occupy various niches within the decomposition food web. Many beetles are predators and parasites of other insects found in carcass tissue (e.g. rove beetles, Coleoptera: Staphylinidae), omnivores that capitalize on the availability of carcass tissue and the concentration of insects in a single location, and adventive species that exploit carcasses as an extension of their habitat (Smith 1986). The order in which insects colonize decomposing carcasses is so predictable that insect community composition can be used in forensic analyses (Amendt et al. 2015). By breaking carcasses into smaller fragments, these same insects ensure that materials are more easily processed by microorganisms, thereby being essential for energy and nutrient cycles of decomposing organisms (Barton et al. 2013, Schowalter 2013).

Pollination of Flowers and Dispersal of Seeds

Insect pollination is fundamental to plant evolution (well established). Pollination by insects is an ancient ecological interaction with deep evolutionary roots (Fig. 1B). Fossil evidence indicates that insect pollination predates the origin and radiation of the flowering plants (angiosperms), and that insects were pollinating gymnosperms since at least the Jurassic period roughly 163 million years ago, and possibly earlier (Peña-Kairath et al. 2023, Peris et al. 2025). Insect pollination thus shaped plant reproductive strategies well before angiosperms dominated the earth and played a key role in the foundation and function of most modern terrestrial ecosystems. An estimated 80% to 90% of flowering plants rely on animal pollinators, the overwhelming majority of which (>90%) are

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insects (Ollerton et al. 2011). Recent syntheses also suggest that roughly 40% of the approximately 900 living gymnosperms rely wholly or partly on insects for pollination (Peña-Kairath et al. 2023).

Pollination maintains genetic diversity, population persistence, and community stability of insect-pollinated plants that underpin ecosystem function (well established). By facilitating pollen transfer among spatially separated or even isolated individual plants, insect pollinators reduce inbreeding, increase effective population size, and enhance adaptive potential for insect-pollinated plants. Declines in pollinator abundance and diversity are well-documented (Brunet and Fragoso 2024) which can reduce plant reproductive success (Artamendi et al. 2025) in part due to reduced genetic diversity. Loss of insect pollinators may result in erosion of genetic diversity due to higher rates of autonomous self-pollination that occur as a form of "reproductive assurance" in the absence of sufficient insect visitation (Barrett and Harder 2017). Genetic bottlenecks arising from self-pollination can reduce plant fitness and resilience, thereby increasing vulnerability to pests, pathogens, and climatic extremes. Loss of insect pollinators can also result in lower fruit and seed set, reduced seed quality, and altered recruitment (Rodger et al. 2021). Over long timescales, these changes could translate into plant population declines and local extinctions, especially for rare or specialist species. At a global scale, these effects threaten not only individual populations and species, but also the structure and stability of plant communities, with cascading impacts on ecosystem function such as primary productivity, carbon and nutrient cycling, and habitat for other organisms. Because insect-pollinated plants dominate nearly all terrestrial biomes, pollinator declines are a pervasive risk to biodiversity worldwide (Rech et al. 2016).

Global food security is sustained by insect pollination (well established). More than three-quarters of leading global crops benefit from animal pollination (Klein et al. 2007, Siopa et al. 2024), the vast majority of which are pollinated by insects. Insect pollinators contribute not only to crop yields, but also to yield stability, crop quality, and nutritional value, especially for fruits, vegetables, nuts, and oilseeds that are central to human diets (Ellis et al. 2015, Woodcock et al. 2019). The role of insects in crop pollination is especially critical in low-and middle-income countries where pollinator-dependent crops support smallholder livelihoods and local food systems, particularly in the tropics (Millard et al. 2023). Declines in pollinator abundance can result in low crop yields and increase variability in yields (Bishop et al. 2022), with disproportionate impacts on regions already exposed to food insecurity and climate stress. Recent meta-analyses indicate that current pollination services are mostly sufficient to maintain global crop yields (Gazzea et al. 2023), however, this masks substantial regional and crop-specific shortfalls (Lander et al. 2025). Many crops are also increasingly reliant on pollination by a limited subset of managed pollinators (Sáez et al. 2022), making them vulnerable to the impacts of global change. Continued erosion of wild pollinator diversity risks undermining the resilience of agricultural systems to future change, including extreme weather events, emerging pests, and land use change (Millard et al. 2021). Safeguarding insect pollinator populations is thus increasingly recognized as a global priority for sustainable agriculture, biodiversity conservation, and human health and well-being (Ollerton 2021).

Ants, and other insects, are critical primary and secondary seed dispersers for many terrestrial plants (established but incomplete). Seed dispersal by insects (Fig. 1C) benefits plants by moving seeds away from parents to high-quality microsites, enabling colonization of new areas and facilitating protection from seed predators (Howe and Smallwood 1982, Schupp et al. 2010). Ants are especially important insect seed dispersers (Penn and Crist 2018), as many are involved in myrmecochory–a mutualism in which seeds have adaptations that entice ants which function as their primary dispersers (Bronstein et al. 2006, Giladi 2006). Approximately 11,000 plant species, across diverse lineages, are myrmecochores, with high concentrations of myrmecochory in shrublands of South Africa and Australia, and in temperate forests in Eurasia and North America (Lengyel et al. 2010). These myrmecochores produce seeds with nutrient-rich appendages called elaiosomes that ants remove after dispersing seeds, leaving seeds intact either in ant nests or deposited nearby. Typically, very few ant species are responsible for the vast majority of seed dispersal for myrmecochores in an ecosystem (Giladi 2006, Ness et al. 2009, Warren and Giladi 2014) and this degree of specialization makes plant communities sensitive to changes in ant assemblages (Rodriguez-Cabal et al. 2009, Prior et al. 2015, Warren et al. 2017). For example, after invasive ants displaced native ants in the South African fynbos ecosystem, the plant community shifted as well (Christian 2001). Despite feeding on seeds, several seed-harvesting ants will also disperse seeds that they drop or cache, which can benefit plant communities especially in desert and grassland ecosystems (Penn and Crist 2018, Uhey and Hofstetter 2022, Rocha et al. 2024). While ants are the primary insect seed dispersers, dung beetles are also important secondary seed dispersers in tropical systems as they roll, move, and bury dung containing seeds (Andresen and Levey 2004, De Vega et al. 2011, DeCastro-Arrazola et al. 2020). More rarely, orthopterans and wasps have been observed moving seeds (Jules 1996, Gomez et al. 2019) and much remains to be discovered about insect-seed interactions.

Formation, Protection, and Decontamination of Soils

Insects and other arthropods are critical for maintaining soil structure and function to support plant health (well established). Globally, arthropods are highly abundant in soil with an estimated biomass of $\sim 1 \times 10^{19}$, of which termites, ants, and arthropods closely related to insects (e.g. mites and springtails) dominate (Rosenberg et al. 2023). Arthropods contribute to the maintenance and stability of soil health via their feeding and burrowing behaviors. Feeding by soil arthropods contributes to the fragmentation and recycling of organic matter in brown food webs, as they decompose living and dead plant material, animal carcasses, and feces (Lavelle et al. 2006). As arthropods begin to transform these materials, they increase the surface area available to microbes, which stimulates mineralization by bacteria and fungi in the soil and increases nutrient availability for plants (Beare et al. 1995, Lavelle et al. 2006). These direct and indirect interactions among microbial communities and arthropods help to maintain stability in soil organic matter pools, including the rates of nitrogen and carbon cycling (Wolters 2000). The burrowing activity of arthropods creates tunnels within the soil profile, and these behaviors

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improve soil structure for plant growth (Lee and Foster 1991). Termites (Blattodea: Isoptera), ants (Hymenoptera: Formicidae), and dung beetles (Coleoptera: Scarabaeidae) have substantial impacts on the physical, chemical, and biological properties of soil due to their roles as ecosystem engineers (Folgarait 1998, Bang et al. 2005, Jouquet et al. 2006). Some species of ants and termites maintain subterranean colonies. The creation and maintenance of these nests mix soil layers, reduce soil compaction, increase porosity and water holding capacity, and improve water infiltration into the soil (Fig. 1D; Lobry de Bruyn and Conacher 1990, Frouz and Jilkova 2008, Govorushko 2019).

Insects are useful indicators of soil contamination and assessment of remediation, but their role in bioremediation is underused (established but incomplete). Insects are commonly used as bioindicators of contamination from anthropogenic activities such as development, industry, and agriculture because of their critical roles in soil structure and function, including decomposition and nutrient cycling, and their importance in soil food webs (Santorufo et al. 2012, Nsengimana et al. 2018). Their roles in bioremediation of contaminated or degraded soils have received less attention, but recent research highlights the potential for entomoremediation by ecosystem engineers (e.g. ants, termites, dung beetles) (Hefft et al. 2022), ground beetles (Tőzsér et al. 2019), black soldier fly (*Hermetia illucens* Linneaus 1758; Diptera: Stratiomyidae) larvae (Raksasat et al. 2020, Bulak et al. 2021), larvae of *Propsilocerus akamusi* (Tokunaga 1938) (Diptera: Chironomidae) (Zheng et al. 2024), and larvae of the mealworm (*Tenebrio molitor* Linneaus 1758; Coleoptera: Tenebrionidae) (Bulak et al. 2021). This process of entomoremediation relies on the ability of these insects to either bioaccumulate and sequester contaminants within their body tissues or biotransform the compounds through digestive enzymes and associated microbiota (van Gestel 2012, Gwenzi et al. 2024). Entomoremediation has been assessed for contamination from heavy metals, plastics including microplastics, and various organic pollutants such as pesticides (Gwenzi et al. 2024).

Regulation of Climate and Energy Cycles

Carbon cycling at a global scale is influenced by insects' effects on decomposition processes (well established). Lignin and cellulose are the most abundant components of plant leaf litter and account for more than half of the carbon sequestered in plant materials. Decomposition of cellulose and dead plant materials by insects (Fig. 2A) drives carbon and nitrogen cycling, linking belowground process with aboveground productivity and carbon sequestration (Lavelle et al. 1997). Deadwood and leaf litter account for approximately 8% and 4%, respectively, of the global forest carbon stock (Pan et al. 2024). The net effect of insects on wood decomposition accounts for 29% of the carbon flux from deadwood globally (Seibold et al. 2021). Much of this decomposition originates in tropical forests, which have high deadwood carbon stocks, climatic conditions that favor high metabolic rates and insect activity, and high insect biodiversity including many termite species that are major contributors to wood decomposition (Seibold et al. 2021, Zanne et al. 2022). At the global scale, roughly 31% of leaf litter decomposition is mediated by insects and other invertebrates, with especially strong effects in tropical and subtropical forests (38% on average) compared to temperate and boreal forests (26% on average) with substantial regional variation (Zeng et al. 2024). Insects generally increase the rate of wood decomposition by 10% to 40% depending on the system (Ulyshen 2016, Njoroge et al. 2025), however, the rate of decomposition is directly influenced by the presence, abundance, diversity, and community composition of insects. For example, the diversity and abundance of beetle species increases wood decomposition rates directly and indirectly by altering fungal communities (Zou et al. 2023), however, species identity also matters as some beetles can introduce fungi that lower the overall decomposition rate (Skelton et al. 2020). Similarly, leaf litter decomposition rates are strongly affected by the functional diversity of invertebrates, rather than by species richness alone (Heemsbergen et al. 2004) suggesting that individual species play key roles.

Carbon release and sequestration due to insect activity have shifted as a result of global change (established but incomplete). Forest disturbances caused by insects have increased dramatically worldwide (Kautz et al. 2017, Miguel et al. 2026). Past increases in disturbance were driven by climate change and ecosystem modifications by humans (Seidl et al. 2017). For instance, in Central Europe, conifers were widely planted during the 20th century on sites that have since become unsuitable for conifers under shifting climate conditions (Seidl et al. 2011). In North America, trees are more susceptible to insect outbreaks due to decades of fire suppression which produced dense forests with heightened resource stress (Fettig et al. 2022). Large-scale bark beetle outbreaks have been increasing more rapidly than other disturbance agents such as wind or fire in recent decades (Kurz et al. 2008, Hlásny et al. 2021, Kärvemo et al. 2023, Patacca et al. 2023). Insect disturbances are likely to continue increasing under climate change, potentially causing fundamental shifts in tree species composition (Grünig et al. 2026). Following a bark beetle disturbance, carbon sequestration is immediately reduced for several years because photosynthesis is limited by foliage, however, compared to other disturbance agents, the release of carbon following insect outbreaks is relatively slow (Kurz et al. 2008, Hicke et al. 2013). Insect disturbances result in standing deadwood, which decomposes slowly compared to fallen trees on the forest floor, and it can take years or even decades before carbon release after an insect disturbance equals that after windthrows or forest fires (Fettig et al. 2022). The revitalization of an ecosystem after an insect disturbance may even lead to medium- to long-term increases in carbon sequestration, but the potential for carbon uptake is heavily dependent on future climate scenarios, tree species composition, and forest structural characteristics (Thom et al. 2022).

Insect activities transport nutrients across habitat boundaries (well established). Insects frequently play an important role in the movement of nutrients between terrestrial and freshwater ecosystems (Nowlin et al. 2007, Gratton et al. 2008, Sato et al. 2011a, 2011b, Hoekman et al. 2012, Raitif et al. 2019). Emergence of aquatic insects (Fig. 2B) represents a substantial flux of nutrients from aquatic to terrestrial ecosystems. It is estimated that the deposition of midges (Diptera: Chironomidae) near lake shores amounts to 10 kg of nitrogen per hectare per year, and 1 kg of phosphorus per hectare per year (Dreyer et al. 2012). This nutrient influx scales up to affect ecosystems. At lakes that have high midge abundance, shoreline plants have upwards of 10% more nitrogen content than lakes with low midge abundance, and caterpillars are not

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only more abundant but also much larger (Bultman et al. 2014) potentially providing more food to insectivorous birds (Grames et al. 2023). Because many insects emerge en masse, the flux of carbon and other nutrients from aquatic to terrestrial habitats represents a major resource pulse (Walters et al. 2018). There is also increasing evidence that aerial movements of insects at high altitudes can represent a substantial biomass transport over long distances (Hu et al. 2016, Satterfield et al. 2020).

Decomposition of plant and animal matter by insects is critical for nutrient cycling in terrestrial and aquatic ecosystems (well established). As biomass transformers, insects play a key role in the decomposition and cycling of plant biomass (Frost and Hunter 2004, Yang 2006, Metcalfe et al. 2014). Insect herbivory increases rates of nutrient cycling in nearly all terrestrial ecosystems, including tropical forests (Metcalfe et al. 2014, Zeng et al. 2024), Arctic tundra (Kaukonen et al. 2013, Koltz et al. 2018a), grasslands (Belovsky and Slade 2000, Nitschke et al. 2015), and arid and desert environments (Sagi and Hawlena 2021). Invertebrate presence in terrestrial ecosystems increases wood decomposition by 10% to 40% depending on the system, largely driven by insect activities, especially termites (Ulyshen 2016, Njoroge et al. 2025). The effects of insects on the breakdown and processing of organic matter in aquatic ecosystems are also well established (Vanni 2002, Marks 2019, Benbow et al. 2020, Asad et al. 2025). In streams, insect shredders physically break down leaves and other plant matter, process small plant particles as collectors (Marks 2019), and can break down wood (Braccia and Batzer 2008) but their importance is less well known than other functional groups.

Insect nutrient cycling affects, and is affected by, climate change (inconclusive). Climate change is likely to affect the ecosystem services provided by insects, including nutrient cycling, in many ways (Yang et al. 2021a, Vidal et al. 2025). Elevated temperatures associated with climate change are likely to increase litter decomposition rates in aquatic ecosystems (Amani et al. 2019), but the specific role of insects in this shift is unclear. Studies have demonstrated that invertebrates can mediate warming effects on decomposition rates in terrestrial ecosystems (Koltz et al. 2018b), however, the generality of this effect is unclear.

Regulation of Freshwater Quality

Aquatic insects serve as bioindicators of water quality (well established). Because some aquatic insects are highly sensitive to environmental conditions, their presence in water bodies, particularly in streams, is often used as an indicator of water quality (Fig. 2D; Macadam and Stockan 2015, Suter and Cormier 2015). Water pollution is multifaceted, and monitoring water quality through water samples can introduce biases such as the time of survey, and requires detailed assessments for hundreds of chemicals. Aquatic insects are present in water for long periods of time, and can provide a better, more reliable picture of water quality at a site than water samples. Different insect taxa are also known to have varying levels of tolerance to water quality conditions, and the community composition present at a site can indicate the type of impairment (Friberg et al. 2011). While water quality indices using bioindicators often vary regionally, many rely on the diversity of mayflies, stoneflies, and caddisflies (Ephemeroptera, Plecoptera, and Trichoptera) as many species in these orders are intolerant of pollutants in their juvenile, aquatic stages (DeWalt and Ower 2019, Jacobus et al. 2019, Morse et al. 2019) and they can be monitored easily with help from community scientists (Resh 2007). Moreover, by analyzing adult aquatic insects for heavy metals, they can indicate not only water quality, but also the level of sediment contamination (Macadam and Stockan 2015, Manjula et al. 2024). Preliminary work also indicates that aquatic insects may be useful bioindicators for the presence of microplastic pollution (Nel et al. 2018, Khdre et al. 2023, Benhadji et al. 2025).

Insects reduce eutrophication and increase water clarity (well established). The addition of nutrients, primarily nitrogen and phosphorus, to waterbodies can result in algal blooms (Smith and Schindler 2009) which have negative impacts on water quality, human health, and the economy (Dodds et al. 2009, Hillborn and Beasley 2015, Wurtsbaugh et al. 2019). Aquatic insects play a key role in limiting eutrophication in freshwater ecosystems. Due to their abundance and biomass, aquatic insects retain a large proportion of the nutrients in freshwater ecosystems in their tissues, limiting the amount of nitrogen and phosphorus present in the water column and available to algae (Suter and Cormier 2015). Many of these insects transform into terrestrial adults that die and decompose in terrestrial ecosystems (Gratton and Vander Zanden 2009, Greenwood and Booker 2016), thereby removing those nutrients from rivers and lakes. In the case of non-biting midges (Diptera: Chironomidae) and burrowing mayflies (Ephemeroptera: Ephemeridae) this can represent a vast movement of nutrients out of aquatic ecosystems (Suter and Cormier 2015, Adler and Courtney 2019). Moreover, some non-biting midge and burrowing mayfly larvae create burrows in the sediment that remove phosphorus (Hupfer et al. 2019) and nitrogen (Yang et al. 2021b, Jiang et al. 2024) from the water column, increasing the effectiveness of eutrophication control measures (Severiano et al. 2023), but evidence for this is still inconclusive (Chaffin and Kane 2010, Leslie and Lamp 2019, Michael et al. 2023). Many aquatic insects filter water to gain nutrients (Wallace and Merrit 1980) which not only reduces eutrophication, but also removes sediment particles from the water column (Wotton and Malmqvist 2001, Adler and Courtney 2019, Morse et al. 2019), increasing water clarity (Suter and Cormier 2015).

Insects may reduce plastic pollution in freshwater ecosystems (inconclusive). Preliminary evidence suggests that aquatic insect processing of materials may help break down and export microplastics from freshwater ecosystems (Drummond et al. 2025, Ma et al. 2025). This is an emerging field of research and the general impacts of insects on plastic pollution remediation are unclear.

Regulation of Hazards and Extreme Events

Aquatic insects promote ecosystem resilience to storms (inconclusive). Insects increase substrate stability in freshwater ecosystems. Net spinning caddisfly and black fly larvae connect substrate sediment particles with their silk, which reduces suspended solids in streams (Fig. 2C) under ambient conditions and during storm events (Adler and Courtney 2019, Morse et al. 2019). Silk tubes created by non-biting midge larvae also stabilize lake sediments (Edwards 1962, Ólafsson and Paterson 2004, Statzner 2012, Hölker et al. 2015). How these ecosystem

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functions scale up to ecosystem resilience under increasing frequency and severity of storms under climate change is unclear.

Regulation of Organisms Detrimental to Humans

Predatory and parasitoid insects are important contributors to agricultural and forest pest management (well established). Many insects are "natural enemies" that exert top down trophic pressure on pest populations via direct predation or parasitism thereby regulating pest abundance (Fig. 2F). A meta-analysis of the effects of biological control to increase predatory and parasitoid insects found overall positive effects on crop yield, reductions in crop damage, and decreases in pest abundance (Ratto et al. 2022). These "natural enemies" often respond favorably to increased landscape complexity (Chaplin-Kramer et al. 2011, Shackelford et al. 2013) More recently, non-consumptive effects of natural enemies on pest populations have been documented, such as disrupting feeding activities that alleviates negative impacts on crop yields even with no change in the abundance of the pest population (Ali et al. 2025). Actions that positively affect natural enemies result in greater benefits from this ecosystem service, though results depend on the landscape context (Karp et al. 2018, Crowther et al. 2023). This service can be particularly important in regions where pesticides are unavailable or too expensive, especially for smallholder farms.

Aquatic insects regulate disease vector populations (established but incomplete). Many aquatic insects, particularly Odonata (dragonflies and damselflies), are predators of disease vectors such as mosquito larvae (Fig. 2E; Shaalan and Canyon 2009). While Odonata are the most highly effective insects at regulating populations of disease vectors (Priyadarshana and Slade 2023), insects from many orders function as vector control, separately, or in combination with, other taxa (Staats et al. 2016). Most evidence on the effectiveness of insects at controlling disease vectors comes from lab trials which may not accurately reflect prey preferences in nature, as many potential predators of disease vectors are polyphagous (Shaalan and Canyon 2009), however, results indicate that insects are capable of controlling vector population in lab settings. Full-scale ventures to suppress mosquito larvae through the use of insects as vector control have also been implemented in urban settings from Myanmar (Sebastian et al. 1990) to the United States (Lubelczyk et al. 2020).

Insects reduce disease transmission through removal of dead biomass (established but incomplete). Disease risk, and disease transmission, are both lowered by sanitation services provided by insects (Sands and Wall 2017). Many disease vectors for either humans or livestock are transmitted via animal feces, such as bacteria and nematodes. Dung removal by coprophagous species, including insects, reduces the amount of animal feces present in an area, reducing disease transmission and health costs. Dung beetle activities also alter the chemical and physical attributes of dung in ways that limit parasite survival (Fincher 1973).

Provision of Energy

Insects provide critical pollination and pest regulation services for biofuel crops (well established) and may increase biofuel production efficiency (inconclusive). The global energy portfolio increasingly includes agriculturally-derived biofuels (IPCC 2018), many of which are derived from crops that rely on ecosystem services provided by insects. Annual and perennial biofuel crops both rely on insects, especially pest regulation by predators and parasitoids, and pollination for the subset of biofuel crops that benefit from animal pollination. The diversity and abundance of predators, pollinators, and other insects are typically higher in perennial bioenergy systems than in annuals (Werling et al. 2011, 2014, Immerzeel et al. 2014, Núñez-Regueiro et al. 2021, Tudge et al. 2021, Haan et al. 2023). As such, predation and pollination rates by beneficial insects are also higher within perennial crops (Werling et al. 2014, Haan and Landis 2023) which can be enhanced with plant diversity within the cropping system (Haan et al. 2023). Moreover, peptides produced in the digestive tracts of herbivorous insects enable conversion of plant biomass into biofuels (Fu et al. 2024), potentially increasing the efficiency of plant-based biofuel production as well. For instance, termite-derived enzymes have been used to degrade lignin and increase the efficiency of converting cellulose to sugar in bioethanol production (Ke et al. 2010).

Insect-based biofuels are a promising green energy alternative (inconclusive). Biofuels have traditionally been derived from plants, however, insects have recently emerged as an alternative biofuel source that require less land and water, and release fewer pollutants than biofuel crop production (Mohan et al. 2026). Many insects have high lipid content, rapid growth rates, and will feed on waste products (Fig. 3F), making them viable to rear for biodiesel production while also reducing agricultural waste (Manzano-Agugliaro et al. 2012). Black soldier fly larvae (*H. illucens*) in particular have been studied for their potential as a biodiesel source because they have extremely high conversion efficiency to biodiesel and can be reared on kitchen waste or animal manure (Wong et al. 2018). Insect oils can be converted to biodiesel, while waste products from the production process such as frass can be converted to biogas (Mohan et al. 2026). Biofuels derived from *H. illucens* and other insects have the potential to serve as sustainable energy sources and are expected to increase in use in coming decades as global energy demand increases and production becomes more efficient (Prather and Laws 2018).

Insects as Food and Feed

Entomophagy is a long-standing cultural practice (well established). There are more than 2,000 edible insect species consumed globally (Fig. 3E), with the highest diversity of edible insects occurring in tropical regions (Omuse et al. 2024). In many places, entomophagy has deep cultural and historical roots embedded within local and Indigenous knowledge systems (Olivadese and Dindo 2023). As a cultural practice, entomophagy reflects sustainable harvesting practices and seasonal ecological knowledge (Hlongwane et al. 2020). Harvesting edible insects in cultures that practice entomophagy plays a significant role in enhancing food security (Kelemu et al. 2015), generating income, and fostering social identity. These practices are increasingly threatened by climate change, habitat loss, overharvesting, and changing diets, which collectively erode both the insect biodiversity underpinning entomophagy, as well as cultural diversity (Hlongwane et al. 2020).

Insects are a critical alternative protein source for humans and animals (established but incomplete). While entomophagy

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is an established practice in many cultures, in Western cultures it has recently gained traction as a source of both food and animal feed. Recent studies have found that insects are a source of high-quality protein, essential amino acids, polyunsaturated fatty acids, vitamins, and minerals, and often have a superior nutritional yield relative to environmental footprint ratio when compared to conventional livestock (Anyasi et al. 2025). The production of insects requires far less land, water, and feed than conventional livestock, while also emitting fewer greenhouse gases, thereby contributing to climate-smart food systems (Abbasi 2025). In addition to direct human consumption, insects are increasingly being used as an alternative protein source for animal feed, especially for aquaculture and poultry production (Shah et al. 2022). Species such as the black soldier fly (*H. illucens*) and yellow mealworm (*T. molitor*) can be mass-reared on organic waste streams as livestock feed, while also contributing to nutrient cycling and circular bioeconomies (Ganesan et al. 2024). This sector is expanding rapidly, driven by technological innovation, regulatory advancements, and increasing investor interest in sustainable protein alternatives.

Key food resources humans depend on are reliant on insects (well established). Insects are fundamental components of terrestrial and freshwater food webs that directly and indirectly support wild and free-ranging animals that humans rely on as food resources (Schoenly et al. 1991, Yang and Gratton 2014). Given their abundance and nutrient content, insects are prey for a wide variety of organisms consumed by people via subsistence hunting and as bushmeat, such as rodents (Ivanter et al. 2015), bats (Feldhamer et al. 2009), frogs (Solé and Rödder 2010), and reptiles (Pough 1973). In regions with regulated hunts, insects are consumed by some of the most important game birds such as ducks (Einarsson and Gardarsson 2004). Similarly, free-ranging domesticated birds such as chickens opportunistically feed on insects (Coletta et al. 2012). Perhaps most notably, insects comprise the majority of biomass in the diets of many freshwater fishes (Grant 2001) and crayfish (Alcorlo et al. 2004), that feed on both freshwater insects and terrestrial insects at the water surface. Fish that rely heavily on insects include common game fish such as bass and sunfish (Sammons 2012), as well as commercially harvested species such as migratory salmon which gain over half of their energy intake from insects in their juvenile stages (Kawaguchi and Nakano 2001).

Materials and Assistance

Products derived from insects have been used by humans for centuries in textiles, dyes, cosmetics, and crafts (well established). Silk is perhaps the most famous insect-derived product in human history (Fig. 3B). Produced by the silkworm, (*Bombyx mori* Linnaeus 1758), it has been used by humans for well over seven thousand years (Yang et al. 2014) to produce textiles, played a major role in global trade for much of human history, and continues to be used for diverse purposes ranging from clothing and decor to medicine. Insects have also been used to produce dyes for textiles and cosmetics (Serrano et al. 2015). Carmine, also called cochineal extract, is a pigment derived from a scale insect (*Datylopius coccus* Costa 1835) used for centuries as a natural, vibrant red dye. It is used in fabrics and as a food coloring, but is perhaps best known for its use in cosmetics such as lipsticks and blushes (Akçay 2024). Another scale insect (*Kermes vermilio* Planchon 1864) was similarly used to produce a scarlet dye for centuries and is the namesake of the color vermillion. Lac, a resin derived from the lac bug (*Kerria lacca* Kerr 1782), was first used as a material and red dye in India over five thousand years ago. Shellac has been used throughout its history as a wax seal, food dye, a varnish for wood paneling, to produce vinyl records, manufacture ballet shoes, polish violins and other string instruments, and in many other diverse products, all of which depend on the lac bug (Fig. 3A, Ahuja and Rastogi 2023). Beeswax similarly has had numerous uses throughout history, including for candle-making, cosmetics, and as a preservative or lubricant.

Insect-derived materials have the potential to transform medicine (established but incomplete). Cantharidin, derived from blister beetles (Coleoptera: Meloidae), is a known treatment for *Molluscum* infections and is being studied for its anticancer mechanisms (Kok et al. 2006). Other secondary metabolites derived from insects are potentially also valuable materials for modern medicine and warrant further study (Anal et al. 2025). For instance, American cockroaches (*Periplaneta americana* Linnaeus 1758) produce compounds that exhibit cytotoxic activity against cancer cells (Luo et al. 2014), several ant species produce anti-inflammatory compounds (Tang et al. 2015), a compound derived from grasshoppers induces apoptosis in leukemia cells (Griffin et al. 2010), and a compound found in stink bugs reduces kidney disease (Yan et al. 2014). Chitin and its derivative chitosan (Fig. 3C), both of which are derived from insect exoskeletons, have wide applications in medicine including drug delivery and as a wound dressing (Parhi 2020).

Medicinal, Biochemical, and Genetic Resources

Insects are indispensable biomedical model organisms (well established). Due to their low cost, rapid breeding and short generation times, limited space needs, and suitability for large-scale genetic manipulation, insects have facilitated many medical breakthroughs. Flies (Victor Atoki et al. 2025), beetles (Adamski et al. 2019), and moths (Ahlawat and Sharma 2023) all have frequently studied model taxa, with additional species expected to serve as future biomedical models as genomic characterization expands (Feron and Waterhouse 2022). The fruit fly *D. melanogaster* alone accounts for significant biomedical discoveries (Fig. 3D). Sharing over 60% of human genes, *D. melanogaster* has enabled studies of genetic pathways, disease mechanisms, and fundamental biological processes (Öztürk-Çolak et al. 2024, Victor Atoki et al. 2025). Beyond biomedical discovery, *D. melanogaster* has served as a cornerstone of research in genetics and developmental biology, enabling discoveries related to gene function and inheritance. Homologies between insect and mammalian innate immunity further support their use in *in vivo* toxicity testing and host-pathogen research (Piatek et al. 2021).

Thousands of compounds derived from insects are used in traditional and modern medicine (established but incomplete). Folkloric and modern medicine indicate hundreds of insect species, from more than 15 orders, are sources of preventive and therapeutic agents (Siddiqui et al. 2023). Insect cell lines are capable of producing complex proteins that are otherwise difficult to synthesize, making them extremely useful for generating protein-based vaccines and therapeutic agents.

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Insect-derived compounds enhance immunity, improve gastro-, neuro-, and cardio-protection, regulate metabolism, promote tissue regeneration, and provide anti-inflammatory, antitumor, and antimicrobial effects (Tanga and Ekesi 2024, Ishara et al. 2025). Moreover, their microbial symbionts—bacteria, fungi, and actinomycetes—produce distinctive bioactive metabolites with complementary therapeutic potential (Baranova et al. 2022, Fan et al. 2025). The chemical diversity of these bioactives is equally impressive (Teixeira et al. 2023, Ishara et al. 2025). The Antimicrobial Peptide Database lists more than 800 invertebrate-derived peptides known to have 32 functional roles in immune defence (Wang et al. 2026). Such peptides are inspiring next-generation antibiotics targeting multidrug-resistant pathogens, including ESKAPE bacteria—a persistent global health threat (Sahoo et al. 2021). Insect-derived peptides with potent antimicrobial activity are being explored as novel therapeutics that could curb antimicrobial resistance (Mylonakis et al. 2016, Manniello et al. 2021). Venom-derived peptides from bees and wasps (Fratini et al. 2017, Laurindo et al. 2024, Bhardwaj et al. 2025), and cantharidin from blister beetles (Zhang et al. 2025) exhibit potent anticancer properties. Honey alone, from both honey bees and stingless bees, has over 200 bioactive compounds with wide-ranging medicinal applications (Hossain et al. 2021, Yupanqui Mieles et al. 2022, Palma-Morales et al. 2023, Azman et al. 2024, Cabezas-Mera et al. 2024).

Insect-derived materials are critical in biomedical engineering (established but incomplete). Insect-derived materials also underpin advances in drug delivery and biomedical engineering. Insect-based nanoparticles improve treatment efficacy (e.g. chemotherapy), acting as complementary therapies or drug delivery facilitators (Shi et al. 2017, Sinha and Choudhury 2024). Common green bottle fly maggots (*Lucilia sericata* Meigen 1826) and their secretions aid wound debridement and infection management (Mohd Zubir et al. 2020). Insect-derived chitin, chitosan, and silk proteins are used to fabricate biocompatible and biodegradable materials for biosensors, tissue repair, and controlled drug release, including vaccine delivery (Mei et al. 2024, Lin et al. 2025). The silkworm, *B. mori*, provides high-yield production of recombinant proteins for diagnostic application (Park 2025), while bioluminescent firefly luciferase remains pivotal in molecular imaging and gene function studies (Thorne et al. 2010).

Learning and Inspiration

Innovations in engineering, materials science, and design are inspired by insects (established but incomplete). The sheer diversity of insects makes them powerful models for innovation (Stork 2018, Eggleton 2020) and have inspired countless advances through bio-inspired design, also called bioinspiration or biomimicry (Benyus 1997, Iouguina et al. 2014, Whitesides 2015). With technological advancements, we can now see, fabricate, and compute at the same scale where many insects exhibit their most remarkable functional adaptations. Advanced imaging tools can reveal the nano- and microstructures that enable insects to stay clean (Nguyen et al. 2014, Bello et al. 2022), stick to ceilings (Gorb 2007), and display brilliant colors (Seago et al. 2009, Snell-Rood 2025). Precision fabrication tools enable us to recreate these structures in the lab and incorporate them into innovative products (Ye et al. 2022, Zhang et al. 2022). Powerful computational models facilitate simulations of individual insect interactions with other species and their environment, spanning from genomes, to brains, to microhabitats, and even global scales (Barron et al. 2015). By studying how insects work, we can create smarter, multifunctional materials, more efficient mechanical systems, and other technologies that are as resilient and adaptable as insects (Wijerathne et al. 2022, March-Pons et al. 2024, Jovchevska et al. 2025, Couzin 2025). Insects are mentors for innovation (Schroeder et al. 2018) from the powerful spring-loaded jump of click beetles (Ribak and Weihs 2011, Bolmin et al. 2021) to the water-repelling and antimicrobial wings of cicadas (Oh et al. 2017, Watson et al. 2017, Bello and Alleyne 2024) and the collective intelligence of honey bees (Britton et al. 2002). With sequencing of additional insect genomes in recent decades (Cameron 2025), there is an increasing number of species with a broader range of traits available to support technological advancements.

Economic Valuation of Ecosystem Services Provided by Insects

Ecosystem services provided by insects to food production are valued at billions of USD annually (established but incomplete). Given the vast diversity of functional roles insects fill and their numerous contributions to people, the total value of the ecosystem services insects provide is inestimable. Yet, estimates for even just a handful of services, often limited to some parts of the world, place the total value of insects' contributions in the billions, if not trillions, of dollars annually. Pollination is the most widely studied service provided by insects from an economic perspective (Potts et al. 2016, Noriega et al. 2018) as there are a range of models to estimate the economic value of pollination (Breeze et al. 2016). The value of insect pollination globally was estimated at €153 billion in 2009 (Gallai et al. 2009). More recently, insect pollination services in Latin America were valued at an estimated $22.95 billion USD per year (Basualdo et al. 2022). In the United States alone, four ecosystem services provided by insects—dung removal, pest regulation, pollination, and recreation—were valued at $57 billion USD annually two decades ago (Losey and Vaughan 2006). For a single fruit—apples—in the United Kingdom, insects improve crop yield and quality such that they add an estimated additional £5.7 million pounds annually to production value (Garratt et al. 2013). Similarly, dung beetles could be saving the livestock industry an estimated £367 million annually (Beynon et al. 2015). While estimates vary tremendously depending on the ecosystem services considered, valuation methods, time period, and geographic scope, there is no doubt that insects provide extremely valuable ecosystem services and that declines in their abundance, biomass, and species richness could have serious economic consequences.

The economic value of agricultural ecosystem services other than pollination are not well understood (inconclusive). While pollination has been the most frequently valued ecosystem service (Noriega et al. 2018), insects contribute to global food production in other economically quantifiable ways. For instance, insects can affect crop values by regulating pests (Naranjo et al. 2015). A few valuation methods have been used, including economic surplus (Letourneau et al. 2015, Zhang et al. 2018) and production functions (King et al. 2025), to show that increasing natural enemy densities, or reducing

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pest pressure, can have significant economic benefits on crop yields in many cereal crops (e.g. Lundin et al. 2021). Increasing the population of natural enemies increases the thresholds for the economic use of pesticides in soybeans (e.g. Zhang and Swinton 2012). Limited empirical data on the relationships between pests and natural enemy species, pests and crop yield response, and the effects of pesticide resistance, however, limit the precision of the estimated economic valuation of pest regulation. Other contributions of insects to agricultural production value, such as antihelminthic services provided by dung beetles (Beynon et al. 2015), are even less well-studied.

Value ascribed to cultural services provided by insects are geographically and taxonomically biased (inconclusive). Insects provide a range of cultural ecosystem services, including aesthetic value and inspiration for art and music, or by contributing to a sense of identity and community (Ware et al. 2026). Charismatic species such as dragonflies and bees have been studied in the context of cultural value (Macadam and Stockan 2015, Potts et al. 2016), but these services have often been conflated with other values or not monetized. For instance, the public may be willing to pay to avoid declines in pollinator populations (Breeze et al. 2015), but this "existence" value is conflated with the functional value of pollination. Similarly, the public may derive wellbeing from and be willing to pay for both use (recreation) and non-use (existence and bequest) value for bees, beetles, and wasps, though this value may be conflated with pollination and is taxonomically biased (King et al. 2026). Other cultural services, including peoples' love or fear of insects, have not been rigorously identified or quantified (Sumner et al. 2018, Duffus et al. 2021) though entomotourism is a rapidly growing industry (Ware et al. 2026).

Conclusions

Without insects, many populations, communities, and ecosystems would collapse from the loss of supporting services they provide. Many organisms rely on insect ecosystem engineering, such as termite and ant mounds around which many plant and animal populations coalesce due to the concentration of nutrients and structure they provide. As seed dispersers and pollinators, insects regulate plant community assembly patterns, maintain plant genetic diversity and population persistence, and contribute to forest regeneration. Decomposition of animal matter (e.g. dung and carcasses) by insects is critical for dead biomass removal and nutrient cycling, and also reduces disease transmission. Insects, and other arthropods, also maintain soil structure, supporting plant health, food webs, and ecological processes. Many of the critical roles insects play in ecosystem function (e.g. bioremediation and removal of contaminants such as heavy metals and plastic pollution) from ecosystems are just beginning to be fully understood, yet we stand to lose these critical functional roles filled by insects that create and maintain habitats for all life.

The loss of insects would alter global carbon and nutrient cycles, freshwater quality would decline, and there would be explosions of pest and disease vector populations. Insects have always played a critical role in the global carbon cycle, and the flux of carbon through both release (e.g. insects as a forest disturbance agent) and sequestration have shifted as a result of changes in insect communities due to global change. The impacts of insects on global change dynamics is driven largely by their role as decomposers, contributing to nutrient cycling in terrestrial and aquatic ecosystems by breaking down organic matter from deadwood, to leaves, to animal matter. In aquatic ecosystems, this nutrient cycling helps to maintain freshwater quality, as insect activity reduces eutrophication and increases water clarity by filtering nutrients from the water column. Many insects are also sensitive to changes in water quality, and serve as bioindicators used by governments around the world to track the status and trends in freshwater quality. By modifying soil and serving as pollinators and seed dispersers for terrestrial plants, insects may even contribute to ecosystem resilience and stability in the face of increasing frequency and intensity of storms, though their role in this key regulating service is understudied. Many more contributions of insects to earth system processes are not quantified, but can be inferred from their key roles in supporting plant and animal populations whose roles in these processes are well established.

If insects continue to decline in abundance and diversity, humanity will suffer from the loss of provisioning services, with reductions in the global food supply and decreased food security, stagnation in development of green energy, and loss of materials used in engineering, medicine, and materials science. Insects provide essential pollination services to more than three-quarters of crops, contributing to crop yields, maintaining genetic diversity of crops, and ensuring food production to meet global food needs. Insect-based biofuels are an emerging source of renewable energy that promise to have a lower carbon footprint and use far less water than other sources. Insects also pollinate many of the world's biofuel plant crops. We would also lose the potential future scientific and technical advancements we gain from insect-inspired design, research using insects as model organisms, and from bioprospecting compounds produced by the vast diversity of insect life. Insect model organisms have been the cornerstone of genetic research for decades and there is immense untapped potential among the diversity of insects for understanding genetic architecture of diseases and other pressing problems. Their diversity of form and function have inspired material scientists, engineers, and innovators to develop new technologies and methods that improve human lives. The loss of insect biodiversity, abundance, and biomass would have enormous consequences for humanity through reductions in food security, energy, and innovation, as well as severe economic repercussions. The total value of insect ecosystem services is nearly incalculable, and estimated values exceeding hundreds of billions of dollars annually are likely severely underestimated given the many contributions insects make to people, and the many irreplaceable roles they fill. It is imperative that conservation actions be taken and policies implemented to safeguard the diversity of insect life and the many contributions they make to people.

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Conflicts of Interest

None declared.

References

Abbasi E. 2025. Edible insects as a sustainable and innovative approach to addressing global food security and environmental challenges: a comprehensive review. *J. Insects Food Feed* 11:2255–2266. https://doi.org/10.1163/23524588-Bja10208

Adamski Z, Bufo SA, Chowański S, et al. 2019. Beetles as model organisms in physiological, biomedical, and environmental studies-a review. *Front. Physiol.* 10:319. https://doi.org/10.3389/fphys.2019.00319

Adler PH, Courtney GW. 2019. Ecological and societal services of aquatic Diptera. *Insects* 10:70. https://doi.org/10.3390/insects10030070

Ahlawat S, Sharma KK. 2023. Lepidopteran insects: emerging model organisms to study infection by enteropathogens. *Folia Microbiol. (Praha)* 68:181–196. https://doi.org/10.1007/s12223-022-01014-y

Ahuja A, Rastogi VK. 2023. Shellac: from isolation to modification and its untapped potential in the packaging application. *Sustainability* 15:3110. https://doi.org/10.3390/su15043110

Alcorlo P, Geiger W, Marina O. 2004. Feeding preferences and food selection of the red swamp crayfish, *Procambarus clarkii*, in habitats differing in food item diversity. *Crustac. Int. J. Crustac. Res.* 77:435–453. https://doi.org/10.1163/1568540041643283

Ali J, Tonğa A, Yusuf A, et al. 2025. Natural enemy-derived volatiles induce non-consumptive negative effects on the pest aphid, *Myzus persicae*. *Entomologia* 45:1091–1099. https://doi.org/10.1127/entomologia/3420

Akçay AA. 2024. The use of insect pigment in art works. *Insects* 15:519. https://doi.org/10.3390/insects15070519

Amani M, Graça MAS, Ferreira V. 2019. Effects of elevated atmospheric CO_2 concentration and temperature on litter decomposition in streams: a meta-analysis. *Internat Rev Hydrobiol.* 104:14–25. https://doi.org/10.1002/iroh.201801965

Amendt J, Anderson G, Campoasso CP., et al. 2015. Standard Practices. In: Tomberlin JK, Benbow ME, editors. *Forensic entomology: international dimensions and frontiers*. 1st Edition. CRC Press. 381–398.

Anal JMH, Mozhui L, Rokhum SL. 2025. Unveiling the therapeutic potential of insect-derived natural products for drug discovery. *Futur. J. Pharm. Sci.* 11:2. https://doi.org/10.1186/s43094-024-00758-3

Andresen E, Levey DJ. 2004. Effects of dung and seed size on secondary dispersal, seed predation, and seedling establishment of rain forest trees. *Oecologia* 139:45–54. https://doi.org/10.1007/s00442-003-1480-4

Anjos DV, Leal LC, Jordano P, et al. 2020. Ants as diaspore removers of non-myrmecochorous plants: a meta-analysis. *Oikos* 129:775–786. https://doi.org/10.1111/oik.06940

Anyasi TA, Acharya P, Udenigwe CC. 2025. Edible insects as an alternative protein source: nutritional composition and global consumption patterns. *Future Foods* 12:100699. https://doi.org/10.1016/j.fufo.2025.100699

Artamendi M, Martin PA, Bartomeus I, et al. 2025. Loss of pollinator diversity consistently reduces reproductive success for wild and cultivated plants. *Nat. Ecol. Evol.* 9:296–313. https://doi.org/10.1038/s41559-024-02595-2

Asad I, Hussain M, Fatima A, et al. 2025. Aquatic ecosystem and insects: a scientific review of assessing the ecological role of insects in freshwater ecosystems. *Biologia (Lahore)* 71:6–18. https://doi.org/10.17582/journal.Biologia/2025/71.1.06.18

Azman ANSS, Tan JJ, Abdullah MNH, et al. 2024. Medicinal activities of Tualang honey: a systematic review. *BMC Complement. Med. Ther.* 24:358. https://doi.org/10.1186/s12906-024-04664-2

Bang HS, Joon-ho L, Kwon OS, et al. 2005. Effects of paracoprid dung beetles (Coleoptera: Scarabaeidae) on the growth of pasture herbage and on the underlying soil. *Appl. Soil Ecol* 29:165–171. https://doi.org/ https://doi.org/10.1016/j.apsoil.2004.11.001

Downloaded from academic.oup.com/aesa/advance-article/doi/10.1093/aesa/saag038/8943813 by guest on 21 October 2026

Baranova AA, Zakalyukina YV, Ovcharenko AA, et al. 2022. Antibiotics from insect-associated actinobacteria. *Biology. (Basel)* 11:1676. https://doi.org/10.3390/biology11111676

Barrett SCH, Harder LD. 2017. The ecology of mating and its evolutionary consequences in seed plants. *Annu. Rev. Ecol. Evol. Syst.* 48:135–157. https://doi.org/10.1146/annurev-ecolsys-110316-023021

Barron AB, Gurney KN, Meah LFS, et al. 2015. Decision-making and action selection in insects: inspiration from vertebrate-based theories. *Front. Behav. Neurosci.* 9:216. https://doi.org/10.3389/fnbeh.2015.00216

Barton PS, Cunningham SA, Lindenmayer DB, et al. 2013. The role of carrion in maintaining biodiversity and ecological processes in terrestrial ecosystems. *Oecologia* 171:761–772. https://doi.org/10.1007/s00442-012-2460-3

Basualdo M, Cavigliasso P, de Avila , RSJr, et al. 2022. Current status and economic value of insect-pollinated dependent crops in Latin America. *Ecol. Econ* 196:107395. https://doi.org/10.1016/j.ecolecon.2022.107395

Beare MH, Coleman DC, Crossley DAJr, et al. 1995. A hierarchical approach to evaluating the significance of soil biodiversity to biogeochemical cycling. *Plant Soil* 170:5–22. https://doi.org/10.1007/BF02183051

Bello E, Alleyne M. 2024. Brochosome size variation and its influence on leafhopper (Hemiptera: Cicadellidae) wing wettability. *J. Insect Sci.* 24:6. https://doi.org/10.1093/jisesa/ieae003

Bello E, Chen Y, Alleyne M. 2022. Staying dry and clean: an insect's guide to hydrophobicity. *Insects* 14:42. https://doi.org/10.3390/insects14010042

Belovsky GE, Slade JB. 2000. Insect herbivory accelerates nutrient cycling and increases plant production. *Proc. Natl. Acad. Sci. U S A* 97:14412–14417. https://doi.org/10.1073/pnas.250483797

Benbow ME, Receveur JP, Lamberti GA. 2020. Death and decomposition in aquatic ecosystems. *Front. Ecol. Evol.* 8:17. https://doi.org/10.3389/fevo.2020.00017

Benhadji N, Kurniawan SB, Imron MF. 2025. Review of mayflies (Insecta: Ephemeroptera) as a bioindicator of heavy metals and microplastics in freshwater. *Sci. Total Environ.* 958:178057. https://doi.org/10.1016/j.scitotenv.2024.178057

Benyus JM. 1997. *Biomimicry: innovation inspired by nature*. Harper Collins.

Beynon SA, Wainwright WA, Christie M. 2015. The application of an ecosystem services framework to estimate the economic value of dung beetles to the UK cattle industry. *Ecol. Entomol* 40:124–135. https://doi.org/10.1111/een.12240

Bhardwaj V, Thakur N, Kumari P. 2025. Harnessing bee venom for inflammatory diseases management: from traditional medicine to nanotechnology. *Naunyn. Schmiedebergs. Arch. Pharmacol.* 398:9797–9815. https://doi.org/10.1007/s00210-025-03991-6

Bishop J, Garratt MPD, Nakagawa S. 2022. Animal pollination increases stability of crop yield across spatial scales. *Ecol. Lett.* 25:2034–2047. https://doi.org/10.1111/ele.14069

Bolmin O, Socha JJ, Alleyne M, et al. 2021. Nonlinear elasticity and damping govern ultrafast dynamics in click beetles. *Proc. Natl. Acad. Sci. USA.* 118:e2014569118. https://doi.org/10.1073/pnas.2014569118

Braack LEO. 1987. Community dynamics of carbon-attendant arthropods in tropical African woodland. *Oecologia* 72:402–409. https://doi.org/10.1007/BF00377571

Braccia A, Batzer DP. 2008. Breakdown and invertebrate colonization of dead wood in wetland, upland, and river habitats. *Can. J. For. Res.* 38:2697–2704. https://doi.org/10.1139/X08-113

Breeze TD, Bailey AP, Potts SG, et al. 2015. A stated preference valuation of the non-market benefits of pollination services in the UK. *Ecol. Econ* 111:76–85. https://doi.org/10.1016/j.ecolecon.2014.12.022

Breeze TD, Gallai N, Garibaldi LA, et al. 2016. Economic measures of pollination services: shortcomings and future directions. *Trends Ecol. Evol.* 31:927–939. https://doi.org/10.1016/j.tree.2016.09.002

Britton NF, Franks NR, Pratt SC, et al. 2002. Deciding on a new home: how do honeybees agree? *Proc. R Soc. Lond. B* 269:1383–1388. https://doi.org/10.1098/rspb.2002.2001

Brondizio E, Díaz SM, Settele J, et al. 2019. Assessing a planet in transformation: rationale and approach of the IPBES Global Assessment on Biodiversity and Ecosystem Services. In: Brondizio ES, Settele J, Díaz S, et al. Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat. 1–48.

Bronstein JL, Alarcon R, Geber M. 2006. The evolution of plant–insect mutualisms. *New Phytol.* 172:412–428. https://doi.org/10.1111/j.1469-8137.2006.01864.x

Brunet J, Fragoso FP. 2024. What are the main reasons for the worldwide decline in pollinator populations? *CABI Rev* 19:1. https://doi.org/10.1079/cabireviews.2024.0016

Bulak P, Proc K, Pytlak A, et al. 2021. Biodegradation of different types of plastics by *Tenebrio molitor* insect. *Polymers. (Basel)* 13:3508. https://doi.org/10.3390/polym13203508

Bultman H, Hoekman D, Dreyer J, et al. 2014. Terrestrial deposition of aquatic insects increases plant quality for insect herbivores and herbivore density. *Ecol. Entomol* 39:419–426. https://doi.org/10.1111/een.12118

Bump JK, Peterson RO, Vucetich JA. 2009a. Wolves modulate soil nutrient heterogeneity and foliar nitrogen by configuring the distribution of ungulate carcasses. *Ecol* 90:3159–3167. https://doi.org/10.1890/09-0292.1

Bump JK, Webster CR, Vucetich JA, et al. 2009b. Ungulate carcasses perforate ecological filters and create biogeochemical hotspots in forest herbaceous layers allowing trees a competitive advantage. *Ecosyst* 12:996–1007. https://doi.org/10.1007/s10021-009-9274-0

Buse J, Entling MH. 2020. Stronger dung removal in forests compared with grassland is driven by trait composition and biomass of dung beetles. *Ecol. Entom* 45:223–231. https://doi.org/10.1111/een.12793

Cabezas-Mera F, Cedeño-Pinargote AC, Tejera E, et al. 2024. Antimicrobial activity of stingless bee honey (Tribe: Meliponini) on clinical and foodborne pathogens: a systematic review and meta-analysis. *Food Front.* 5:964–993. https://doi.org/10.1002/fft2.386

Cameron SL. 2025. Insect mitochondrial genomics: a decade of progress. *Annu. Rev. Entomol.* 70:83–101. https://doi.org/10.1146/annurev-ento-013024-015553

Chaffin JD, Kane DD. 2010. Burrowing mayfly (Ephemeroptera: Ephemeridae: *Hexagenias* spp.) bioturbation and bioirrigation: a source of internal phosphorus loading in Lake Erie. *J. Great Lakes Res.* 36:57–63. https://doi.org/10.1016/j.jglr.2009.09.003

Chaplin-Kramer R, O'Rourke ME, Blitzer EJ, et al. 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecol. Lett.* 14:922–932. https://doi.org/10.1111/j.1461-0248.2011.01642.x

Christian CE. 2001. Consequences of biological invasion reveal the importance of mutualisms for plant communities. *Nature* 413:635–639. https://doi.org/10.1038/35098093

Coletta LD, Pereira AL, Coelho AAD, et al. 2012. Barn vs. free-range chickens: differences in their diets determined by stable isotopes. *Food Chem* 131:155–160. https://doi.org/10.1016/j.foodchem.2011.08.051

Colwell RK, Guzman LM, Steinke D, et al. 2026. Constructing a lower-bound estimate of the global number of insect species on a hyperdiverse empirical foundation. *Proc. Natl. Acad. Sci. USA.* 123:e2524283123.

Cooke R, Grames EM, Ollerton J., et al. 2026. The consequences of changing insect abundance and diversity for vertebrates. *Nat Rev Biodiv*. https://doi.org/10.1038/s44358-026-00201-w

Couzin ID. 2025. Collective intelligence in animals and robots. *Nat. Commun.* 16:9574. https://doi.org/10.1038/s41467-025-65814-9

Crespo-Perez V, Kazakau E, Roubik DW, et al. 2020. The importance of insects on land and in water: a tropical view. *Curr. Opin. Insect Sci.* 40:31–38. https://doi.org/10.1016/j.cois.2020.05.016

Crowther L, Wilson K, Wilby A. 2023. The impact of field margins on biological pest control: a meta-analysis. *BioControl* 68:387–396. https://doi.org/10.1007/s10526-023-10205-6

Downloaded from academic.oup.com/aesa/advance-article/doi/10.1093/aesa/saag038/8943813 by guest on 21 October 2026

DeCastro-Arrazola I, Hortal J, Noriega J, et al. 2020. Assessing the functional relationship between dung beetle traits and dung removal, burial and seedling emergence. *Ecology*. 101:e03138. https://doi.org/10.1002/ecy.3138

De Vega C, Arista M, Ortiz P, et al. 2011. Endozoochory by beetles: a novel seed dispersal mechanism. *Ann. Bot*. 107:629–637. https://doi.org/10.1093/aob/mcr013

DeWalt RE, Ower GD. 2019. Ecosystem services, global diversity, and rate of stonefly species descriptions (Insecta: Plecoptera). *Insects* 10:99. https://doi.org/10.3390/insects10040099

Dodds WK, Bouska WW, Eitzmann JL, et al. 2009. Eutrophication of US freshwaters: analysis of potential economic damage. *Environ. Sci. Technol*. 43:12–19. https://doi.org/10.1021/es801217q

Dreyer J, Hoekman D, Gratton C. 2012. Lake-derived midges increase abundance of shoreline terrestrial arthropods via multiple trophic pathways. *Oikos* 121:252–258. https://doi.org/10.1111/j.1600-0706.2011.19588.x

Drummond LO, de Oliveira AC, De Grande S, et al. 2025. Microplastic bioaccumulation in odonata larvae: integrating evidence from experimental studies in freshwater microcosm. *Chemosphere* 390:144716. https://doi.org/10.1016/j.chemosphere.2025.144716

Duffus NE, Christie CR, Morimoto J. 2021. Insect cultural services: how insects have changed our lives and how can we do better for them. *Insects* 12:377. https://doi.org/10.3390/insects12050377

Edwards RW. 1962. Some effects of plants and animals on the conditions in fresh-water streams with particular reference to their oxygen balance. In: Southgate BA. Advances in Water Pollution Research: Proceedings of the First International Conference, London, September 1962. Pergamon. 319–333.

Eggleton P. 2020. The state of the world's insects. *Annu. Rev. Environ. Resour*. 45:61–82. https://doi.org/10.1146/annurev-environ-012420-050035

Einarsson A, Gardarsson A. 2004. Moulting diving ducks and their food supply. *Aquat. Ecol* 38:297–307. https://doi.org/10.1023/B:AECO.0000032055.49860.6f

Eldridge D, Pickard J. 1993. Effects of ants on sandy soils in semi-arid eastern Australia - local distribution of nest entrances and their effect on infiltration of water. *Soil. Res*. 31:509–518. https://doi.org/10.1071/SR9930509

Ellis AM, Myers SS, Ricketts TH. 2015. Do pollinators contribute to nutritional health? *PLoS One*. 10:e0114805. https://doi.org/10.1371/journal.pone.0114805

Fan F, Wang Z, Luo Q, et al. 2025. Medical potential of insect symbionts. *Insects* 16:457. https://doi.org/10.3390/insects16050457

Farji-Brener AG, Werenkraut V. 2017. The effects of ant nests on soil fertility and plant performance: a meta-analysis. *J. Anim. Ecol*. 86:866–877. https://doi.org/10.1111/1365-2656.12672

Feldhamer GA, Carter TC, Whitaker JO.Jr 2009. Prey consumed by eight species of insectivorous bats from southern Illinois. *Am. Midl. Nat*. 162:43–51. https://doi.org/10.1674/0003-0031-162.1.43

Feron R, Waterhouse RM. 2022. Exploring new genomic territories with emerging model insects. *Curr. Opin. Insect Sci*. 51:100902. https://doi.org/10.1016/j.cois.2022.100902

Fettig CJ, Runyon JB, Homicz CS, et al. 2022. Fire and insect interactions in North American forests. *Curr. Forestry Rep*. 8:301–316. https://doi.org/10.1007/s40725-022-00170-1

Fincher GT. 1973. Dung beetles as biological control agents for gastrointestinal parasites of livestock. *J. Parasitol* 59:396–399. https://doi.org/10.2307/3278842

Folgarait PJ. 1998. Ant biodiversity and its relationship to ecosystem functioning: a review. *Biodiv. Conserv*. 7:1221–1244. https://doi.org/10.1023/A:1008891901953

Forister ML, Pelton EM, Black SH. 2019. Declines in insect abundance and diversity: we know enough to act now. *Conservat. Sci. Prac*. 1:e80. https://doi.org/10.1111/csp2.80

Fratini F, Cilia G, Turchi B, et al. 2017. Insects, arachnids and centipedes venom: a powerful weapon against bacteria. A literature review. *Toxicon* 130:91–103. https://doi.org/10.1016/j.toxicon.2017.02.020

Friberg N, Bonada N, Bradley DC., et al. 2011. Biomonitoring of human impacts in freshwater ecosystems: the good, the bad and the ugly. In: Woodward G, editor. *Advances in ecological research*, 44. Academic Press. 1–68.

Frost CJ, Hunter MD. 2004. Insect canopy herbivory and frass deposition affect soil nutrient dynamics and export in oak mesocosms. *Ecology*. 85:3335–3347. https://doi.org/10.1890/04-0003

Frouz J, Jilková V. 2008. The effect of ants on soil properties and processes (Hymenoptera: Formicidae). *Myrmecol. News* 11:191–199.

Fu C, Shah AA, Alissa M, et al. 2024. Exploring the potential of insect gut microbes for advancing renewable energy production. *J. Applied Entomology* 148:928–937. https://doi.org/10.1111/jen.13311

Gallai N, Salles J-M, Settele J, et al. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecol. Econ*. 68:810–821. https://doi.org/10.1016/j.ecolecon.2008.06.014

Ganesan AR, Mohan K, Kandasamy S, et al. 2024. Food waste-derived black soldier fly (*Hermetia illucens*) larval resource recovery: a circular bioeconomy approach. *Process Saf. Environ. Prot*. 184:170–189. https://doi.org/10.1016/j.psep.2024.01.084

Garratt MPD, Truslove L, Coston D, et al. 2013. Pollination deficits in UK apple orchards. *J. Pollin. Ecol*. 12:9–14. https://doi.org/10.26786/1920-7603(2014)8

Gazzea E, Batáry P, Marini L. 2023. Global meta-analysis shows reduced quality of food crops under inadequate animal pollination. *Nat. Commun*. 14:4463. https://doi.org/10.1038/s41467-023-40231-y

Giladi I. 2006. Choosing benefits or partners: a review of the evidence for the evolution of myrmecochory. *Oikos* 112:481–492. https://doi.org/10.1111/j.0030-1299.2006.14258.x

Gomez JM, Schupp EW, Jordano P. 2019. Synzoochory: the ecological and evolutionary relevance of a dual interaction. *Biol. Rev. Camb. Philos. Soc*. 94:874–902. https://doi.org/10.1111/brv.12481

Gorb SN. 2007. Smooth attachment devices in insects: functional morphology and biomechanics. In: Casas J, Simpson SJ, editors. *Advances in insect physiology*. 34. Academic Press. 81–115.

Govorushko S. 2019. Economic and ecological importance of termites: a global review. *Entomol. Sci*. 22:21–35. https://doi.org/10.1111/ens.12328

Grames EM, Montgomery GA, Youngflesh C, et al. 2023. The effect of insect food availability on songbird reproductive success and chick body condition: evidence from a systematic review and meta-analysis. *Ecol. Lett*. 26:658–673. https://doi.org/10.1111/ele.14178

Grant PM. 2001. Mayflies as food. In: Domingue E, editor. *Trends in research in ephemeroptera and plecoptera*. Springer US. 107–124.

Gratton C, Donaldson J, Vander Zanden MJ. 2008. Ecosystem linkages between lakes and the surrounding terrestrial landscape in northeast Iceland. *Ecosystems* 11:764–774. https://doi.org/10.1007/s10021-008-9158-8

Gratton C, Vander Zanden MJ. 2009. Flux of aquatic insect productivity to land: comparison of lentic and lotic ecosystems. *Ecology*. 90:2689–2699. https://doi.org/10.1890/08-1546.1

Greenwood MJ, Booker DJ. 2016. Influence of hydrological regime and land cover on traits and potential export capacity of adult aquatic insects from river channels. *Ecosyst. Ecol*. 180:551–566. https://doi.org/10.1007/s00442-015-3462-8

Griffin C, Hamm C, McNulty J, et al. 2010. Pancratistatin induces apoptosis in clinical leukemia samples with minimal effect on non-cancerous peripheral blood mononuclear cells. *Cancer Cell Int*. 10:6. https://doi.org/10.1186/1475-2867-10-6

Grünig M, Rammer W, Baumann M., et al. 2026. Loss of competitive strength in European conifer species under climate change. bioRxiv. https://doi.org/10.64898/2026.02.13.705703

Gwenzi W, Gufe C, Alufasi R, et al. 2024. Insects to the rescue? Insights into applications, mechanisms, and prospects of insect-driven remediation of organic contaminants. *Sci. Total Environ*. 925:171116. https://doi.org/10.1016/j.scitotenv.2024.171116

Downloaded from academic.oup.com/aesa/advance-article/doi/10.1093/aesa/saag038/8943813 by guest on 21 October 2026

Haan NL, Benucci GMN, Fiser C, et al. 2023. Contrasting effects of bioenergy crops on biodiversity. *Sci. Adv*. 9:eadh7960. https://doi.org/10.1126/sciadv.adh7960

Haan NL, Landis DA. 2023. Pest suppression potential varies across 10 bioenergy cropping systems. *GCB Bioenerg*. 15:765–775. https://doi.org/10.1111/gcbb.13053

Hanski I, Cambefort Y. 1991. *Dung beetle ecology*. Princeton University Press.

Heemsbergen DA, Berg MP, Loreau M, et al. 2004. Biodiversity effects on soil processes explained by interspecific functional dissimilarity. *Science* 306:1019–1020. https://doi.org/10.1126/science.1101865

Hefft DI, Anani OA, Aigbodion F, et al. 2022. Ex situ studies on *Macrotermes bellicosus* as a potential bioremediation tool of polluted dump soil sites for Sub Saharan Africa. *Soil. Sediment. Contam*. 31:855–873. https://doi.org/10.1080/15320383.2021.2017402

Hicke JA, Meddens AJH, Allen CD, et al. 2013. Carbon stocks of trees killed by bark beetles and wildfire in the western United States. *Environ. Res. Lett*. 8:035032. 035032. https://doi.org/10.1088/1748-9326/8/3/035032

Hillborn ED, Beasley VR. 2015. One health and cyanobacteria in freshwater systems: animal illnesses and deaths are sentinels of human health risks. *Toxins. (Basel)* 7:1374–1395. https://doi.org/10.3390/toxins7041374

Hlásny T, Zimová S, Merganičová K, et al. 2021. Devastating outbreak of bark beetles in the Czech Republic: drivers, impacts, and management implications. *For. Ecol. Manage*. 490:119075. https://doi.org/10.1016/j.foreco.2021.119075

Hlongwane ZT, Slotow R, Munyai TC. 2020. Indigenous knowledge about consumption of edible insects in South Africa. *Insects*. 12:22. https://doi.org/10.3390/insects12010022

Hoekman D, Bartrons M, Gratton C. 2012. Ecosystem linkages revealed by experimental lake-derived isotope signal in heathland food webs. *Oecologia* 170:735–743. https://doi.org/10.1007/s00442-012-2329-5

Hölker F, Vanni MJ, Kuiper JJ, et al. 2015. Tube-dwelling invertebrates: tiny ecosystem engineers have large effects in lake ecosystems. *Ecol. Monogr*. 85:333–351. https://doi.org/10.1890/14-1160.1

Holt JA, Lepage M. 2000. Termites and soil properties. In: Abe T, Bignell DE, Higashi M. *Termites: evolution, sociality, symbioses, ecology*. Kluwer Academic Publishers. 398-407.

Hossain ML, Lim LY, Hammer K, et al. 2021. Honey-based medicinal formulations: a critical review. *Appl. Sci*. 11:5159. https://doi.org/10.3390/app11115159

Howe HF, Smallwood J. 1982. Ecology of seed dispersal. *Annu. Rev. Ecol. Syst*. 13:201–228. https://doi.org/10.1146/annurev.es.13.110182.001221

Hu G, Lim KS, Horvitz N, et al. 2016. Mass seasonal bioflows of high-flying insect migrants. *Science* 354:1584–1587. https://doi.org/10.1126/science.aah4379

Hupfer M, Jordan S, Herzog C, et al. 2019. Chironomid larvae enhance phosphorus burial in lake sediments: insights from long-term and short-term experiments. *Sci. Total Environ*. 663:254–264. https://doi.org/10.1016/j.scitotenv.2019.01.274

Immerzeel DJ, Verweij PA, van der Hilst F, et al. 2014. Biodiversity impacts of bioenergy crop production: a state-of-the-art review. *GCB Bioenerg*. 6:183–209. https://doi.org/10.1111/gcbb.12067

Iouguina A, Dawson JW, Hallgrímsson B, et al. 2014. Biologically informed disciplines: a comparative analysis of bionics, biomimetics, biomimicry, and bio-inspiration among others. *Int. J. DNE*. 9:197–205. https://doi.org/10.2495/DNE-V9-N3-197-205

IPCC. 2018. *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Cambridge University Press. https://doi.org/.1017/9781009157940

Ishara J, Ekaette I, Matendo R, et al. 2025. Potential health benefits of insect bioactive metabolites and consumer attitudes towards edible insects. *NPJ Sci. Food*. 9:195. https://doi.org/10.1038/s41538-025-00549-x

Ivanter EV, Korosov AV, Makarov AM. 2015. Study of the trophic relations of small insectivorous mammals. *Biol. Bull. Russ. Acad. Sci*. 42:845–856. https://doi.org/10.1134/S1062359015090058

Jacobus LM, Macadam CR, Sartori M. 2019. Mayflies (Ephemeroptera) and their contributions to ecosystem services. *Insects* 10:170. https://doi.org/10.3390/insects10060170

Jiang Q, Shrivastava S, Jin G, et al. 2024. Enhanced removal of river-borne nitrate in bioturbated hyporheic zone. *Geophys. Res. Lett*. 51:e2024GL108673. https://doi.org/10.1029/2024GL108673

Jordano P. 2000. Fruits and frugivory. In: Fenner M, editors. *Seeds: the ecology of regeneration in plant communities*. 2nd ed. CAB International. 125–166.

Jouquet P, Dauber J, Lagerlöf J, et al. 2006. Soil invertebrates as ecosystem engineers: intended and accidental effects on soil and feedback loops. *Appl. Soil Ecol*. 32:153–164. https://doi.org/10.1016/j.apsoil.2005.07.004

Jovchevska M, Jayaram K, Xu N. 2025. Multimodal locomotion in insect-inspired microrobots: a review of strategies for aerial, surface, aquatic, and interfacial motion. *Adv. Rob. Res*. 0:e202500113. https://doi.org/10.1002/adrr.202500113

Jules ES. 1996. Yellow jackets (*Vespula vulgaris*) as a second seed disperser for the myrmecochorous plant, *Trillium ovatum*. *Am. Midl. Nat*. 135:367–369. https://doi.org/10.2307/2426720

Kamaru DN, Palmer TM, Riginos C, et al. 2024. Disruption of an ant-plant mutualism shapes interactions between lions and their primary prey. *Science* 383:433–438. https://doi.org/10.1126/science.adg1464

Karp DS, Chaplin-Kramer R, Meehan TD, et al. 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. *Proc. Natl. Acad. Sci. U S A* 115:e7863–e7870. https://doi.org/10.1073/pnas.1800042115

Kärvemo S, Huo L, Öhrn P, et al. 2023. Different triggers, different stories: bark-beetle infestation patterns after storm and drought-induced outbreaks. *For. Ecol. Manag*. 545:121255. https://doi.org/10.1016/j.foreco.2023.121255

Kaukonen M, Ruotsalainen AL, Wali PR, et al. 2013. Moth herbivory enhances resource turnover in subarctic mountain birch forests? *Ecology*. 94:267–272. https://doi.org/10.1890/12-0917.1

Kautz M, Meddens AJ, Hall RJ, et al. 2017. Biotic disturbances in Northern Hemisphere forests-a synthesis of recent data, uncertainties and implications for forest monitoring and modelling. *Global Ecol. Biogeogr*. 26:533–552. https://doi.org/10.1111/geb.12558

Kawaguchi Y, Nakano S. 2001. Contribution of terrestrial invertebrates to the annual resource budget for salmonids in forest and grassland reaches of a headwater stream. *Freshw. Biol*. 46:303–316. https://doi.org/10.1046/j.1365-2427.2001.00667.x

Ke J, Sun JZ, Nguyen HD, et al. 2010. In-situ oxygen profiling and lignin modification in guts of wood-feeding termites. *Insect Sci*. 17:277–290. https://doi.org/10.1111/j.1744-7917.2010.01336.x

Kelemu S, Niassy S, Torto B, et al. 2015. African edible insects for food and feed: inventory, diversity, commonalities and contribution to food security. *JIFF*. 1:103–119. https://doi.org/10.3920/JIFF2014.0016

Khdre AM, Ramadan SA, Ashry A, et al. 2023. *Chironomus* sp. as a bioindicator for assessing microplastic contamination and the heavy metals associated with it in the sediment of wastewater in Sohag Governorate, Egypt. *Water. Air. Soil Pollut*. 234:161. https://doi.org/10.1007/s11270-023-06179-x

King P, Breeze TD, Robinson T, et al. 2026. Heterogeneous preferences for use and non-use values provided by insects. *People Nat*. https://doi.org/10.1002/pan3.70385

King P, Robinson T, Howard C, et al. 2025. Economic valuation of pest regulation benefits provided by arthropods in the UK. *Ecosyst. Serv*. 76:101776. https://doi.org/10.1016/j.ecoser.2025.101776

Downloaded from academic.oup.com/aesa/advance-article/doi/10.1093/aesa/saag038/8943813 by guest on 21 October 2026

Klein AM, Vaissière BE, Cane JH, et al. 2007. Importance of pollinators in changing landscapes for world crops. *Proc. R Soc. B* 274:303–313. https://doi.org/10.1098/rspb.2006.3721

Kok SHL, Chui CH, Lam WS, et al. 2006. Apoptotic activity of a novel synthetic cantharidin analogue on hepatoma cell lines. *Int. J. Mol. Med*. 17:945–949. https://doi.org/10.3892/ijmm.17.5.945

Koltz AM, Asmus A, Gough L, et al. 2018a. The detritus-based microbial-invertebrate food web contributes disproportionately to carbon and nitrogen cycling in the Arctic. *Polar Biol*. 41:1531–1545. https://doi.org/10.1007/s00300-017-2201-5

Koltz AM, Classen AT, Wright JP. 2018b. Warming reverses top-down effects of predators on belowground ecosystem function in Arctic tundra. *Proc. Natl. Acad. Sci. U S A* 115:e7541–e7549. https://doi.org/10.1073/pnas.1808754115

Kurz WA, Dymond CC, Stinson G, et al. 2008. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452:987–990. https://doi.org/10.1038/nature06777

Kurz WA, Stinson G, Rampley GJ, et al. 2008. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proc. Natl. Acad. Sci. U S A* 105:1551–1555. https://doi.org/10.1073/pnas.0708133105

Lander TA, Atta-Boateng A, Toledo-Hernández M, et al. 2025. Global chocolate supply is limited by low pollination and high temperatures. *Comm. Earth. Environ* 6:97. https://doi.org/10.1038/s43247-025-02072-z

Laurindo LF, de Lima EP, Laurindo LF, et al. 2024. The therapeutic potential of bee venom-derived Apamin and Melittin conjugates in cancer treatment: a systematic review. *Pharmacol. Res*. 209:107430. https://doi.org/10.1016/j.phrs.2024.107430

Lavelle P, Bignell D, Lepage M, et al. 1997. Soil function in a changing world: the role of invertebrate ecosystem engineers. *Eur. J. Soil Biol* 33:159–193.

Lavelle P, Decaëns T, Aubert M, et al. 2006. Soil invertebrates and ecosystem services. *Eur. J. Soil Biol*. 42:s3-s15. https://doi.org/10.1016/j.ejsobi.2006.10.002

Lee KE, Foster RC. 1991. Soil fauna and soil structure. *Aust. J. Soil Res* 29:745–775. https://doi.org/10.1071/SR9910745

Lengyel S, Gove AD, Latimer AM, et al. 2010. Convergent evolution of seed dispersal by ants, and phylogeny and biogeography in flowering plants: a global survey. *Perspect. Plant Ecol. Evol. Syst*. 12:43–55. https://doi.org/10.1016/j.ppees.2009.08.001

Leslie AW, Lamp WO. 2019. Burrowing macroinvertebrates alter phosphorus dynamics in drainage ditch sediments. *Aquat. Sci*. 81:23. https://doi.org/10.1007/s00027-019-0621-8

Letourneau DK, Ando AW, Jedlicka JA, et al. 2015. Simple-but-sound methods for estimating the value of changes in biodiversity for biological pest control in agriculture. *Ecol. Econ*. 120:215–225. https://doi.org/10.1016/j.ecolecon.2015.10.015

Levey DJ, Byrne MM. 1993. Complex ant-plant interactions: rain forest ants as secondary dispersers and post-dispersal seed predators. *Ecology* 74:1802–1812. https://doi.org/10.2307/1939938

Lin Y, Zhao L, Jin H, et al. 2025. Multifunctional applications of silk fibroin in biomedical engineering: a comprehensive review on innovations and impact. *Int. J. Biol. Macromol*. 309:143067. https://doi.org/10.1016/j.ijbiomac.2025.143067

Lobry de Bruyn LA, Conacher AJ. 1990. The role of termites and ants in soil modification—a review. *Aust. J. Soil Res*. 28:55–93. https://doi.org/10.1071/SR9900055c

Losey JE, Vaughan M. 2006. The economic value of ecological services provided by insects. *Bioscience*. 56:311–323. https://doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2

Lubelczyk CB, Elias SP, DeMaynadier PG, et al. 2020. Importation of dragonfly nymphs (Odonata: Anisoptera) to control mosquito larvae (Diptera: Culicidae) in Southern Maine. *Northeast. Nat*. 27:330–343. https://doi.org/10.1656/045.027.0214

Lundin O, Rundlöf M, Jonsson M, et al. 2021. Integrated pest and pollinator management–expanding the concept. *Frontiers in Ecol. Environ*. 19:283–291. https://doi.org/10.1002/fee.2325

Luo SL, Huang XJ, Wang Y, et al. 2014. Isocoumarins from American cockroach (Periplaneta americana) and their cytotoxic activities. *Fitoterapia* 95:115–120. https://doi.org/10.1016/j.fitote.2014.03.004

Ma J, Lv C, Gong Z, et al. 2025. Promotion of microplastic degradation on the conjugative transfer of antibiotic resistance genes in the gut of macrobenthic invertebrates. *Ecotoxicol. Environ. Saf*. 293:117999. https://doi.org/10.1016/j.ecoenv.2025.117999

Macadam C, Stockan JA. 2015. More than just fish food: ecosystem services provided by freshwater insects. *Ecol. Entomol*. 40:113–123. https://doi.org/10.1111/een.12245

Manjula KT, Abdul Jaleel K, Vijaya MB, et al. 2024. Dragonflies and damselflies: a comprehensive review on their role as heavy metal bioindicators in aquatic ecosystems. *Environ. Ecol. Res*. 12:419–429. https://doi.org/10.13189/eer.2024.120407

Manniello MD, Moretta A, Salvia R, et al. 2021. Insect antimicrobial peptides: potential weapons to counteract the antibiotic resistance. *Cell. Mol. Life Sci*. 78:4259–4282. https://doi.org/10.1007/s00018-021-03784-z

Manning P, Cutler GC. 2018. Ecosystem functioning is more strongly impaired by reducing dung beetle abundance than by reducing species richness. *Agric. Ecosys. Environ* 264:9–14. https://doi.org/10.1016/j.agee.2018.05.002

Manzano-Agugliaro F, Sanchez-Muros MJ, Barroso FG, et al. 2012. Insects for biodiesel production. *Renewable Sustainable Energy Rev*. 16:3744–3753. https://doi.org/10.1016/j.rser.2012.03.017

March-Pons D, Mugica J, Ferrero EE, et al. 2024. Honeybee-like collective decision making in a kilobot swarm. *Phys. Rev. Res*. 6: 033149. https://doi.org/10.1103/PhysRevResearch.6.033149

Marks JC. 2019. Revisiting the fate of dead leaves that fall into streams. *Annu. Rev. Ecol. Evol. Syst*. 50:547–568. https://doi.org/10.1146/annurev-ecolsys-110218-024755

Mei Z, Kuzhir P, Godeau G. 2024. Update on chitin and chitosan from insects: sources, production, characterization, and biomedical applications. *Biomimetics* 9:297. https://doi.org/10.3390/biomimetics9050297

Metcalfe DB, Asner GP, Martin RE, et al. 2014. Herbivory makes major contributions to ecosystem carbon and nutrient cycling in tropical forests. *Ecol. Lett*. 17:324–332. https://doi.org/10.1111/ele.12233

Michael TC, Costello DM, Fitzgibbon AS, et al. 2023. Invertebrate activities in wetland sediments influence oxygen and nutrient dynamics at the sediment-water interface. *Wetlands* 43:96. https://doi.org/10.1007/s13157-023-01737-9

Miguel S, Lines E, Tanase M, et al. 2026. Unravelling the spatial and temporal variability of natural disturbances in European forests. *J. Appl. Ecol*. 63:e70344. https://doi.org/10.1111/1365-2664.70344

Millard J, Outhwaite CL, Ceauşu S, et al. 2023. Key tropical crops at risk from pollinator loss due to climate change and land use. *Sci. Adv*. 9:eadh0756. https://doi.org/10.1126/sciadv.adh0756

Millard J, Outhwaite CL, Kinnersley R, et al. 2021. Global effects of land-use intensity on local pollinator biodiversity. *Nat. Commun*. 12:2902. https://doi.org/10.1038/s41467-021-23228-3

Milotić T, Baltzinger C, Eichberg C, et al. 2019. Functionally richer communities improve ecosystem functioning: dung removal and secondary seed dispersal by dung beetles in the Western Palaearctic. *J. Biogeog* 46:70–82. https://doi.org/10.1111/jbi.13452

Mohan K, Kandasamy S, Pachiannan T, et al. 2026. Insect-based biofuel: a review on emerging technologies and sustainable energy pathways. *Biomass Bioenerg*. 205:108498. https://doi.org/10.1016/j.biombioe.2025.108498

Mohd Zubir MZ, Holloway S, Mohd Noor N. 2020. Maggot therapy in wound healing: a systematic review. *IJERPH*. 17:6103. https://doi.org/10.3390/ijerph17176103

Moretti TC, Ribeiro OB, Thyssen PJ, et al. 2008. Insects on decomposing carcasses of small rodents in a secondary forest in Southeastern Brazil. *Eur. J. Entomol*. 105:691–696. https://doi.org/10.14411/eje.2008.094

Downloaded from academic.oup.com/aesa/advance-article/doi/10.1093/aesa/saag038/8943813 by guest on 21 October 2026

Morse JC, Frandsen PB, Graf W, et al. 2019. Diversity and ecosystem services of Trichoptera. *Insects*. 10:125. https://doi.org/10.3390/insects10050125

Mylonakis E, Podsiadlowski L, Muhammed M, et al. 2016. Diversity, evolution and medical applications of insect antimicrobial peptides. *Philos. Trans. R Soc. Lond. B Biol. Sci*. 371. https://doi.org/10.1098/rstb.2015.0290

Naranjo SE, Ellsworth PC, Frisvold GB. 2015. Economic value of biological control in integrated pest management of managed plant systems. *Annu. Rev. Entomol*. 60:621–645. https://doi.org/10.1146/annurev-ento-010814-021005

Nel HA, Dalu T, Wasserman RJ. 2018. Sinks and sources: assessing microplastic abundance in river sediment and deposit feeders in an Austral temperate urban river system. *Sci. Total Environ*. 612:950–956. https://doi.org/10.1016/j.scitotenv.2017.08.298

Nervo B, Tocco C, Caprio E, et al. 2014. The effects of body mass on dung removal efficiency in dung beetles. *PLoS One*. 9:e107699. https://doi.org/10.1371/journal.pone.0107699

Ness JH, Morin DF, Giladi I. 2009. Uncommon specialization in a mutualism between a temperate herbaceous plant guild and an ant: *Aphaenogaster* ants keystone mutualists? *Oikos* 118:1793–1804. https://doi.org/10.1111/j.1600-0706.2009.17430.x

Neuschulz EL, Mueller T, Schleuning M, et al. 2016. Pollination and seed dispersal are the most threatened processes of plant regeneration. *Sci. Rep*. 6:29839. https://doi.org/10.1038/srep29839

Nguyen SH, Webb HK, Mahon PJ, et al. 2014. Natural insect and plant micro-/nanostructured surfaces: an excellent selection of valuable templates with superhydrophobic and self-cleaning properties. *Molecules* 19:13614–13630. https://doi.org/10.3390/molecules190913614

Nichols E, Spector S, Louzada J, et al. 2008. Ecological functions and ecosystem services provided by Scarabaeinae dung beetles. *Biol. Cons*. 141:1461–1474. https://doi.org/10.1016/j.biocon.2008.04.011

Nitschke N, Wiesner K, Hilke I, et al. 2015. Increase of fast nutrient cycling in grassland microcosms through insect herbivory depends on plant functional composition and species diversity. *Oikos*. 124:161–173. https://doi.org/10.1111/oik.01476

Njoroge DM, Dossa GG, Schaefer D, et al. 2025. The effects of invertebrates on wood decomposition across the world. *Biol. Rev. Camb. Philos. Soc*. 100:158–171. https://doi.org/10.1111/brv.13134

Noriega JA, Hortal J, Azcárate FM, et al. 2018. Research trends in ecosystem services provided by insects. *Basic Appl. Ecol*. 26:8–23. https://doi.org/10.1016/j.baae.2017.09.006

Noriega JA, March-Salas M, Castillo S, et al. 2021. Human perturbations reduce dung beetle diversity and dung removal ecosystem function. *Biotropica* 53:753–766. https://doi.org/10.1111/btp.12953

Noriega JA, Schowalter TD 2024. Insects as functional components of communities and ecosystems. In: Pryke JS, Samways MJ, New TR., et al., editors. *Routledge handbook of insect conservation*. Routledge. 35–52.

Nowlin WH, González MJ, Vanni MJ, et al. 2007. Allochthonous subsidy of periodical cicadas affects the dynamics and stability of pond communities. *Ecology*. 88:2174–2186. https://doi.org/10.1890/06-0570.1

Nsengimana V, Kaplin BA, Francis F, et al. 2018. Use of soil and litter arthropods as biological indicators of soil quality in forest plantations and agricultural lands: a review. *Entomol. Faun*. 71:1–12. https://doi.org/10.25518/2030-6318.4042

Núñez-Regueiro MM, Siddiqui SF, Fletcher RJ. 2021. Effects of bioenergy on biodiversity arising from land-use change and crop type. *Cons. Biol*. 35:77–87. https://doi.org/10.1111/cobi.13452

Oh J, Dana CE, Hong S, et al. 2017. Exploring the role of habitat on the wettability of cicada wings. *ACS Appl. Mater. Interfaces*. 9:27173–27184. https://doi.org/10.1021/acsami.7b07060

Ólafsson JS, Paterson DM. 2004. Alteration of biogenic structure and physical properties by tube-building chironomid larvae in cohesive sediments. *Aquat. Ecol*. 38:219–229. https://doi.org/10.1023/B:AECO.0000032050.10546.bb

Olivadese M, Dindo ML. 2023. Edible insects: a historical and cultural perspective on entomophagy with a focus on western societies. *Insects*. 14:690. https://doi.org/10.3390/insects14080690

Ollerton J, Winfree R, Tarrant S. 2011. How many flowering plants are pollinated by animals? *Oikos*. 120:321–326. https://doi.org/10.1111/j.1600-0706.2010.18644.x

Ollerton J. 2021. *Pollinators and pollination: nature and society*. Pelagic Publishing.

Omuse ER, Tonnang HEZ, Yusuf AA, et al. 2024. The global atlas of edible insects: analysis of diversity and commonality contributing to food systems and sustainability. *Sci. Rep*. 14:5045. https://doi.org/10.1038/s41598-024-55603-7

Öztürk-Çolak A, Marygold SJ, Antonazzo G, FlyBase Consortium, et al. 2024. FlyBase: updates to the Drosophila genes and genomes database. *Genetics*. 227:iyad211. https://doi.org/10.1093/genetics/iyad211

Palma-Morales M, Huertas JR, Rodríguez-Pérez C. 2023. A comprehensive review of the effect of honey on human health. *Nutrients* 15:3056. https://doi.org/10.3390/nu15133056

Pan Y, Birdsey RA, Phillips OL, et al. 2024. The enduring world forest carbon sink. *Nature*. 631:563–569. https://doi.org/10.1038/s41586-024-07602-x

Parhi R. 2020. Drug delivery applications of chitin and chitosan: a review. *Environ. Chem. Lett*. 18:577–594. https://doi.org/10.1007/s10311-020-00963-5

Park EY. 2025. From silkroad to bioroad-silkworm biotechnology. *Protein Expr. Purif*. 234:106762. https://doi.org/10.1016/j.pep.2025.106762

Parmenter RR, MacMahon JA. 2009. Carrion decomposition and nutrient cycling in a semiarid shrub–steppe ecosystem. *Ecol. Monogr*. 79:637–661. https://doi.org/10.1890/08-0972.1

Patacca M, Lindner M, Lucas-Borja ME, et al. 2023. Significant increase in natural disturbance impacts on European forests since 1950. *Glob. Chang. Biol*. 29:1359–1376. https://doi.org/10.1111/gcb.16531

Peña-Kairath C, Delclòs X, Álvarez-Parra S, et al. 2023. Insect pollination in deep time. *Trends Ecol. Evol*. 38:749–759. https://doi.org/10.1016/j.tree.2023.03.008

Penn HJ, Crist JO. 2018. From dispersal to predation: a global synthesis of ant-seed interactions. *Ecol. Evol*. 8:9122–9138. https://doi.org/10.1002/ece3.4377

Pennisi E. 2015. Africa's soil engineers: termites. *Science*. 347:596–597. https://doi.org/10.1126/science.347.6222.596

Peris D, Ollerton J, Sauquet H, et al. 2025. Evolutionary implications of a deep-time perspective on insect pollination. *Biol. Rev. Camb. Philos. Soc*. 100:1452–1466. https://doi.org/10.1111/brv.70008

Piatek M, Sheehan G, Kavanagh K. 2021. *Galleria mellonella*: the versatile host for drug discovery, in vivo toxicity testing and characterising host-pathogen interactions. *Antibiotics (Basel)* 10:1545. https://doi.org/10.3390/antibiotics10121545

Potts SG, Imperatriz-Fonseca V, Ngo HT, et al. 2016. Safeguarding pollinators and their values to human well-being. *Nature*. 540:220–229. https://doi.org/10.1038/nature20588

Pough FH. 1973. Lizard energetics and diet. *Ecology*. 54:837–844. https://doi.org/10.2307/1935678

Prather CM, Laws AN. 2018. Insects as a piece of the puzzle to mitigate global problems: an opportunity for ecologists. *Basic Appl. Ecol*. 26:71–81. https://doi.org/10.1016/j.baae.2017.09.009

Prior KM, Meadley-Dunphy SA, Frederickson ME. 2020. Interactions between seed-dispersing ant species affect plant community composition in field mesocosms. *J. Anim. Ecol*. 89:2485–2495. https://doi.org/10.1111/1365-2656.13310

Prior KM, Robinson JM, Meadley-Dunphy SA, et al. 2015. Mutualism between co-introduced species facilitates invasion and alters plant community structure. *Proc. Biol. Sci*. 282:20142846. https://doi.org/10.1098/rspb.2014.2846

Downloaded from academic.oup.com/aesa/advance-article/doi/10.1093/aesa/saag038/8943813 by guest on 21 October 2026

Priyadarshana TS, Slade EM. 2023. A meta-analysis reveals that dragonflies and damselflies can provide effective biological control of mosquitoes. *J. Anim. Ecol.* 92:1589–1600. https://doi.org/10.1111/1365-2656.13965

Raitif J, Plantegenest M, Roussel JM. 2019. From stream to land: ecosystem services provided by stream insects to agriculture. *Agric. Ecosyst. Environ.* 270-271:32–40. https://doi.org/10.1016/j.agee.2018.10.013

Raksasat R, Lim JW, Kiatkittipong W, et al. 2020. A review of organic waste enrichment for inducing palatability of black soldier fly larvae: wastes to valuable resources. *Environ. Pollut.* 267:115488. https://doi.org/10.1016/j.envpol.2020.115488

Ratto F, Bruce T, Chipabika G, et al. 2022. Biological control interventions reduce pest abundance and crop damage while maintaining natural enemies in sub-Saharan Africa: a meta-analysis. *Proc. R Soc. B.* 289:20221695. https://doi.org/10.1098/rspb.2022.1695

Rech AR, Dalsgaard B, Sandel B, et al. 2016. The macroecology of animal versus wind pollination: ecological factors are more important than historical climate stability. *Plant Ecol. Divers.* 9:253–262. https://doi.org/10.1080/17550874.2016.1207722

Resh VH. 2007. Multinational, freshwater biomonitoring programs in the developing world: lessons learned from African and Southeast Asian river surveys. *Environ. Manage.* 39:737–748. https://doi.org/10.1007/s00267-006-0151-8

Ribak G, Weihs D. 2011. Jumping without using legs: the jump of the click-beetles (Elateridae) is morphologically constrained. *PLoS One.* 6:e20871. https://doi.org/10.1371/journal.pone.0020871

Richards PJ. 2009. *Aphaenogaster* ants as bioturbators: impacts on soil and slope processes. *Earth. Sci. Rev.* 96:92–106. https://doi.org/10.1016/j.earscirev.2009.06.004

Rocha F, Bogar TA, Weemaels A, et al. 2024. Two sides of the same coin? Ants are ecosystem engineers and providers of ecosystem services. *Myrmecol. News* 34:129–157. https://doi.org/10.25849/myrmecol.news_034:129

Rodger JG, Bennett JM, Razanajatovo M, et al. 2021. Widespread vulnerability of flowering plant seed production to pollinator declines. *Sci. Adv.* 7:eabd3524. eabd3524. https://doi.org/10.1126/sciadv.abd3524

Rodriguez-Cabal MA, Stubble KL, Nunez MA, et al. 2009. Quantitative analysis of the effects of the exotic Argentine ant on seed-dispersal mutualisms. *Biol. Lett.* 5:499–502. https://doi.org/10.1098/rsbl.2009.0297

Rosenberg Y, Bar-On YM, Fromm A, et al. 2023. The global biomass and number of terrestrial arthropods. *Sci. Adv.* 9:eabq4049. https://doi.org/10.1126/sciadv.abq4049

Rosumek FB, Silveira FAO, Neves FD, et al. 2009. Ants on plants: a meta-analysis on the role of ants as plant biotic defenses. *Oecologia* 160:537–549. https://doi.org/10.1007/s00442-009-1309-x

Sáez A, Aguilar R, Ashworth L, et al. 2022. Managed honeybees decrease pollination limitation in self-compatible but not in self-incompatible crops. *Proc. Biol. Sci.* 289:20220086. https://doi.org/10.1098/rspb.2022.0086

Sagi N, Hawlena D. 2021. Arthropods as the engine of nutrient cycling in arid ecosystems. *Insects* 12:726. https://doi.org/10.3390/insects12080726

Sahoo A, Swain SS, Behera A, et al. 2021. Antimicrobial peptides derived from insects offer a novel therapeutic option to combat biofilm: a review. *Front. Microbiol.* 12: 661195. https://doi.org/10.3389/fmicb.2021.661195

Sammons SM. 2012. Diets of juvenile and sub-adult size classes of three Micropterus spp. in the Flint River, Georgia: potential for trophic competition. *Southeast. Nat.* 11:387–404. https://doi.org/10.1656/058.011.0303

Sands B, Wall R. 2017. Dung beetles reduce livestock gastrointestinal parasite availability on pasture. *J. Appl. Ecol.* 54:1180–1189. https://doi.org/10.1111/1365-2664.12821

Santorufo L, Van Gestel CA, Rocco A, et al. 2012. Soil invertebrates as bioindicators of urban soil quality. *Environ. Pollut.* 161:57–63. https://doi.org/10.1016/j.envpol.2011.09.042

Sato T, Watanabe K, Kanaiwa M, et al. 2011. Nematomorph parasites drive energy flow through a riparian ecosystem. *Ecology.* 92:201–207. https://doi.org/10.1890/09-1565.1

Sato T, Watanabe K, Tokuchi N, et al. 2011. A nematomorph parasite explains variation in terrestrial subsidies to trout streams in Japan. *Oikos.* 120:1595–1599. https://doi.org/10.1111/j.1600-0706.2011.19121.x

Satterfield DA, Sillett TS, Chapman JW, et al. 2020. Seasonal insect migrations: massive, influential, and overlooked. *Frontiers in Ecol. Environ.* 18:335–344. https://doi.org/10.1002/fee.2217

Schoenly K, Beaver RA, Heumier TA. 1991. On the trophic relations of insects: a food-web approach. *Am. Nat.* 137:597–638. https://doi.org/10.1086/285185

Schowalter TD. 2013. Insects and decomposition. In: Levin S, editor. *Encyclopedia of biodiversity*. 2nd ed. Academic Press. p. 248–256.

Schroeder TBH, Houghtaling J, Wilts BD, et al. 2018. It's not a bug, it's a feature: functional materials in insects. *Adv. Mater.* 30:e1705322. https://doi.org/10.1002/adma.201705322

Schupp EW, Jordano P, Gomez JM. 2010. Seed dispersal effectiveness revisited: a conceptual review. *New Phytol.* 188:333–353. https://doi.org/10.1111/j.1469-8137.2010.03402.x

Seago AE, Brady P, Vigneron JP, et al. 2009. Gold bugs and beyond: a review of iridescence and structural colour mechanisms in beetles (Coleoptera). *J. R Soc. Interf.* 6:S165–S184. https://doi.org/10.1098/rsif.2008.0354.focus

Sebastian A, Sein MM, Thu MM, et al. 1990. Suppression of *Aedes aegypti* (Diptera: Culicidae) using augmentative release of dragonfly larvae (Odonata: Libellulidae) with community participation in Yangon, Myanmar. *Bull. Entomol. Res.* 80:223–232. https://doi.org/10.1017/S0007485300013468

Seibold S, Rammer W, Hothorn T, et al. 2021. The contribution of insects to global forest deadwood decomposition. *Nature.* 597:77–81. https://doi.org/10.1038/s41586-021-03740-8

Seidl R, Schelhaas MJ, Lexer MJ. 2011. Unraveling the drivers of intensifying forest disturbance regimes in Europe. *Glob. Chang. Biol.* 17:2842–2852. https://doi.org/10.1111/j.1365-2486.2011.02452.x

Seidl R, Thom D, Kautz M, et al. 2017. Forest disturbances under climate change. *Nat. Clim. Chang.* 7:395–402. https://doi.org/10.1038/nclimate3303

Serrano A, van den Doel A, van Bommel M, et al. 2015. Investigation of crimson-dyed fibres for a new approach on the characterization of cochineal and kermes dyes in historical textiles. *Anal. Chim. Acta.* 897:116–127. https://doi.org/10.1016/j.aca.2015.09.046

Severiano JS, Pontes de Lima ER, Lucena-Silva D, et al. 2023. The role of bioturbation triggered by benthic macroinvertebrates in the effectiveness of the Floc & Lock technique in mitigating eutrophication. *Water Res.* 246:120691. https://doi.org/10.1016/j.watres.2023.120691

Shaalan EAS, Canyon DV. 2009. Aquatic insect predators and mosquito control. *Trop. Biomed.* 26:223–261.

Shackelford G, Steward PR, Benton TG, et al. 2013. Comparison of pollinators and natural enemies: a meta-analysis of landscape and local effects on abundance and richness in crops. *Biol. Rev. Camb. Philos. Soc.* 88:1002–1021. https://doi.org/10.1111/brv.12040

Shah AA, Totakul P, Matra M, et al. 2022. Nutritional composition of various insects and potential uses as alternative protein sources in animal diets. *Anim. Biosci.* 35:317–331. https://doi.org/10.5713/ab.21.0447

Shi Z, Song T, Wan Y, et al. 2017. A systematic review and meta-analysis of traditional insect Chinese medicines combined chemotherapy for non-surgical hepatocellular carcinoma therapy. *Sci. Rep.* 7:4355. https://doi.org/10.1038/s41598-017-04351-y

Downloaded from academic.oup.com/aesa/advance-article/doi/10.1093/aesa/saag038/8943813 by guest on 21 October 2026

Siddiqui SA, Li C, Aidoo OF, et al. 2023. Unravelling the potential of insects for medicinal purposes—a comprehensive review. *Heliyon* 9:e15938. https://doi.org/10.1016/j.heliyon.2023.e15938

Sileshi GW, Arshad MA, Konaté S, et al. 2010. Termite-induced heterogeneity in African savanna vegetation: mechanisms and patterns. *J. Veg. Sci.* 21:923–937. https://doi.org/10.1111/j.1654-1103.2010.01197.x

Sinha B, Choudhury Y. 2024. Revisiting edible insects as sources of therapeutics and drug delivery systems for cancer therapy. *Front. Pharmacol.* 15:1345281. https://doi.org/10.3389/fphar.2024.1345281

Siopa C, Carvalheiro LG, Castro H, et al. 2024. Animal-pollinated crops and cultivars—a quantitative assessment of pollinator dependence values and evaluation of methodological approaches. *J. Appl. Ecol.* 61:1279–1288. https://doi.org/10.1111/1365-2664.14634

Skelton J, Loyd A, Smith JA, et al. 2020. Fungal symbionts of bark and ambrosia beetles can suppress decomposition of pine sapwood by competing with wood-decay fungi. *Fungal Ecol.* 45:100926. https://doi.org/10.1016/j.funeco.2020.100926

Slade EM, Riutta T, Roslin T, et al. 2016. The role of dung beetles in reducing greenhouse gas emissions from cattle farming. *Sci. Rep.* 6:18140. https://doi.org/10.1038/srep18140

Smith KGV. 1986. *A manual of forensic entomology*. Cornell University Press.

Smith VH, Schindler DW. 2009. Eutrophication science: where do we go from here? *Trends Ecol. Evol.* 24:201–207. https://doi.org/10.1016/j.tree.2008.11.009

Snell-Rood EC. 2025. The value of basic research: tracing how the wonder of a blue butterfly inspired modern innovation. *J. Exp. Biol.* 228:jeb250118. https://doi.org/10.1242/jeb.250118

Solé M, Rödder D. 2010. Dietary assessments of adult amphibians. In: Dodd CK, editor. *Amphibian ecology and conservation: a handbook of techniques*. Oxford University Press. p. 167–184.

Staats EG, Agosta SJ, Vonesh JR. 2016. Predator diversity reduces habitat colonization by mosquitoes and midges. *Biol. Lett.* 12: 20160580. https://doi.org/10.1098/rsbl.2016.0580

Statzner B. 2012. Geomorphological implications of engineering bed sediments by lotic animals. *Geomorph* 157–158:49–65. https://doi.org/10.1016/j.geomorph.2011.03.022

Stokland JN, Siitonen J, Jonsson BG. 2012. *Biodiversity in dead wood*. Cambridge University Press.

Stork NE. 2018. How many species of insects and other terrestrial arthropods are there on Earth? *Annu. Rev. Entomol.* 63:31–45. https://doi.org/10.1146/annurev-ento-020117-043348

Sumner S, Law G, Cini A. 2018. Why we love bees and hate wasps. *Ecol. Entomol.* 43:836–845. https://doi.org/10.1111/een.12676

Suter , GWII, Cormier SM. 2015. Why care about aquatic insects: uses, benefits, and service. *Integr. Environ. Assess. Manag.* 11:188–194. https://doi.org/10.1002/ieam.1600

Tang JJ, Fang P, Xia HL, et al. 2015. Constituents from the edible Chinese black ants (*Polyrhachis dives*) showing protective effect on rat mesangial cells and anti-inflammatory activity. *Food Res. Int.* 67:163–168. https://doi.org/10.1016/j.foodres.2014.11.022

Tanga CM, Ekesi S. 2024. Dietary and therapeutic benefits of edible insects: a global perspective. *Annu. Rev. Entomol.* 69:303–331. https://doi.org/10.1146/annurev-ento-020123-013621

Teixeira CS, Villa C, Costa J, et al. 2023. Edible insects as a novel source of bioactive peptides: a systematic review. *Foods* 12:2026. https://doi.org/10.3390/foods12102026

Thom D, Jentsch A, Seidl R. 2022. Disturbances and ecosystem services. In: Wohlgemuth T, Jentsch A, Seidl R, editors. *Disturbance ecology*. Springer Nature. 413–433.

Thorne N, Inglese J, Auld DS. 2010. Illuminating insights into firefly luciferase and other bioluminescent reporters used in chemical biology. *Chem. Biol.* 17:646–657. https://doi.org/10.1016/j.chembiol.2010.05.012

Towne EG. 2000. Prairie vegetation and soil nutrient responses to ungulate carcasses. *Oecologia* 122:232–239. https://doi.org/10.1007/PL00008851

Tőzsér D, Magura T, Simon E, et al. 2019. Pollution intensity-dependent metal accumulation in ground beetles: a meta-analysis. *Environ. Sci. Pollut. Res. Int.* 26:32092–32102. https://doi.org/10.1007/s11356-019-06294-5

Tudge SJ, Purvis A, De Palma A. 2021. The impacts of biofuel crops on local biodiversity: a global synthesis. *Biodivers. Conserv.* 30:2863–2883. https://doi.org/10.1007/s10531-021-02232-5

Uhey DHA, Hofstetter RW. 2022. From pests to keystone species: ecosystem influences and human perceptions of harvester ants (*Pogonomyrmex*, *Veromessor*, and *Messor* spp.). *Ann. Entomol. Soc. Am.* 115:127–140. https://doi.org/10.1093/aesa/saab046

Ulyshen MD. 2016. Wood decomposition as influenced by invertebrates. *Biol. Rev. Camb. Philos. Soc.* 91:70–85. https://doi.org/10.1111/brv.12158

van Gestel CAM. 2012. Soil ecotoxicology: state of the art and future directions. *Zookeys*. 176:275–296. https://doi.org/10.3897/zookeys.176.2275

Vander Wall SB, Kuhn KM, Beck MJ. 2005. Seed removal, seed predation, and secondary dispersal. *Ecol* 86:801–806. https://doi.org/10.1890/04-0847

Vanni MJ. 2002. Nutrient cycling by animals in freshwater ecosystems. *Annu. Rev. Ecol. Syst.* 33:341–370. https://doi.org/10.1146/annurev.ecolsys.33.010802.150519

Victor Atoki A, Aja PM, Shinkafi TS, et al. 2025. Exploring the versatility of *Drosophila melanogaster* as a model organism in biomedical research: a comprehensive review. *Fly. (Austin)*. 19:2420453. https://doi.org/10.1080/19336934.2024.2420453

Vidal MC, Abarca M, Backe K, et al. 2025. What do we know about insect responses to global change? A review of meta-analyses on global change drivers. *Insect Conserv. Divers.* 18:900–916. https://doi.org/10.1111/icad.12845

Wagner DL, Grames EM, Forister ML, et al. 2021. Insect decline in the Anthropocene: death by a thousand cuts. *Proc. Natl. Acad. Sci. USA.* 118:e2023989118. https://doi.org/10.1073/pnas.2023989118

Wallace JB, Merrit RW. 1980. Filter-feeding ecology of aquatic insects. *Annu. Rev. Entomol.* 25:103–132. https://doi.org/10.1146/annurev.en.25.010180.000535

Walters DM, Wesner JS, Zuellig RE, et al. 2018. Holy flux: spatial and temporal variation in massive pulses of emerging insect biomass from western US rivers. *Ecology*. 99:238–240. https://doi.org/10.1002/ecy.2023

Wang G, Schmidt C, Li X, et al. 2026. APD6: the antimicrobial peptide database is expanded to promote research and development by deploying an unprecedented information pipeline. *Nucleic Acids Res.* 54:d363–d374. https://doi.org/10.1093/nar/gkaf860

Ware JL, Birrell JH, Elfin J, et al. 2026. Insects and quality of life. https://doi.org/10.1093/aesa/saag039

Warren RJ, Giladi I. 2014. Ant-mediated seed dispersal: a few ant species (Hymentoptera: Formicidae) benefit many plants. *Myrmecol. News* 20:129–140.

Warren RJ, King JR, Chick LD. 2017. Global change impacts on ant-mediated seed dispersal in Eastern North American forests. In: Oliveira PS, Koptur K, editors. *Ant-plant interactions: impacts of humans on terrestrial systems*. Cambridge University Press. p. 93–111.

Watson EJG. 2004. Faunal succession of necrophilous insects associated with high-profile wildlife carcasses in Louisiana. Louisiana State University. https://repository.lsu.edu/gradschool_dissertations/3235

Watson GS, Watson JA, Cribb BW. 2017. Diversity of cuticular micro-and nanostructures on insects: properties, functions, and potential applications. *Annu. Rev. Entomol.* 62:185–205. https://doi.org/10.1146/annurev-ento-031616-035020

Werling BP, Dickson TL, Isaacs R, et al. 2014. Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proc. Natl. Acad. Sci. U S A* 111:1652–1657. https://doi.org/10.1073/pnas.1309492111

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Werling BP, Meehan TD, Robertson BA, et al. 2011. Biocontrol potential varies with changes in biofuel–crop plant communities and landscape perenniality. *GCB Bioenerg*. 3:347–359. https://doi.org/10.1111/j.1757-1707.2011.01092.x

Whitesides GM. 2015. Bioinspiration: something for everyone. *Interface Focus*. 5:20150031. https://doi.org/10.1098/rsfs.2015.0031

Wijerathne B, Liao T, Ostrikov K, et al. 2022. Bioinspired robust mechanical properties for advanced materials. *Small Struct*. 3:2100228. https://doi.org/10.1002/sstr.202100228

Wilson EO. 1987. The little things that run the world (the importance and conservation of invertebrates). *Cons. Biol*. 1:344–346. https://doi.org/10.1111/j.1523-1739.1987.tb00055.x

Woodcock BA, Garratt MPD, Powney GD, et al. 2019. Meta-analysis reveals that pollinator functional diversity and abundance enhance crop pollination and yield. *Nat. Commun*. 10:1481. https://doi.org/10.1038/s41467-019-09393-6

Wolters V. 2000. Invertebrate control of soil organic matter stability. *Biol. Fertil. Soils* 31:1–19. https://doi.org/10.1007/s003740050618

Wong CY, Lim JW, Uemura Y., et al. 2018. Insect-based lipid for biodiesel production. AIP Conf. Proc. 2016:020150. https://doi.org/10.1063/1.5055552

Wotton RS, Malmqvist B. 2001. Feces in aquatic ecosystems: feeding animals transform organic matter into fecal pellets, which sink or are transported horizontally by currents; these fluxes relocate organic matter in aquatic ecosystems. *Bioscience*. 51:537–544. https://doi.org/10.1641/0006-3568(2001)051[0537:FIAE]2.0.CO;2

Wurtsbaugh WA, Paerl HW, Dodds WK. 2019. Nutrients, eutrophication and harmful algal blooms along a freshwater to marine continuum. *WIREs Water* 6:e1373. https://doi.org/10.1002/wat2.1373

Yan YM, Ai J, Shi YN, et al. 2014. (±)-Aspongamide A, an N-Acetyldopamine trimer isolated from the insect *Aspongopus chinensis*, is an inhibitor of p-Smad3. *Org. Lett*. 16:532–535. https://doi.org/10.1021/ol403409v

Yang LH, Gratton C. 2014. Insects as drivers of ecosystem processes. *Curr. Opin. Insect Sci* 2:26–32. https://doi.org/10.1016/j.cois.2014.06.004

Yang LH, Postema EG, Hayes TE, et al. 2021a. The complexity of global change and its effects on insects. *Curr. Opin. Insect Sci*. 47:90–102. https://doi.org/10.1016/j.cois.2021.05.001

Yang LH. 2006. Interactions between a detrital resource pulse and a detritivore community. *Oecologia* 147:522–532. https://doi.org/10.1007/s00442-005-0276-0

Yang SY, Han MJ, Kang LF, et al. 2014. Demographic history and gene flow during silkworm domestication. *BMC Evol. Biol*. 14:185. https://doi.org/10.1186/s12862-014-0185-0

Yang W, Yao J, He Y, et al. 2021b. Nitrogen removal enhanced by benthic bioturbation coupled with biofilm formation: a new strategy to alleviate freshwater eutrophication. *J. Environ. Manage*. 292:112814. https://doi.org/10.1016/j.jenvman.2021.112814

Ye X, Li Y, Zhang Y, et al. 2022. A comprehensive review: recent developments of biomimetic sensors. *J. Bionic Eng*. 19:853–876. https://doi.org/10.1007/s42235-022-00181-5

Yupanqui Mieles J, Vyas C, Aslan E, et al. 2022. Honey: an advanced antimicrobial and wound healing biomaterial for tissue engineering applications. *Pharmaeutics* 14:1663. https://doi.org/10.3390/pharmaceutics14081663

Zanne AE, Flores-Moreno H, Powell JR, et al. 2022. Termite sensitivity to temperature affects global wood decay rates. *Science* 377:1440–1444. https://doi.org/10.1126/science.abo3856

Zeng X, Gao H, Wang R, et al. 2024. Global contribution of invertebrates to forest litter decomposition. *Ecol. Lett*. 27:e14423. e14423. https://doi.org/10.1111/ele.14423

Zhang H, Garratt MP, Bailey A, et al. 2018. Economic valuation of natural pest control of the summer grain aphid in wheat in South East England. *Ecosyst. Serv* 30:149–157. https://doi.org/10.1016/j.ecoser.2018.02.019

Zhang J, Tian T, Li C, et al. 2025. Cantharidin: a double-edged sword in medicine and toxicology. *Front. Pharmacol*. 16:1644186. https://doi.org/10.3389/fphar.2025.1644186

Zhang S, Ke X, Jiang Q, et al. 2022. Fabrication and functionality integration technologies for small-scale soft robots. *Adv. Mater*. 34:e2200671. 2200671. https://doi.org/10.1002/adma.202200671

Zhang W, Swinton SM. 2012. Optimal control of soybean aphid in the presence of natural enemies and the implied value of their ecosystem services. *J. Environ. Manage*. 96:7–16. https://doi.org/10.1016/j.jenvman.2011.10.008

Zheng X, Li Y, Xu J, et al. 2024. Response of *Propsilocerus akamusi* (Diptera: Chironomidae) to the leachates from AMD-contaminated sediments: implications for metal bioremediation of AMD-polluted areas. *Aquat. Toxicol*. 266:106795. https://doi.org/10.1016/j.aquatox.2023.106795

Zou JY, Cadotte MW, Bässler C, et al. 2023. Wood decomposition is increased by insect diversity, selection effects, and interactions between insects and microbes. *Ecology*. 104:e4184. https://doi.org/10.1002/ecy.4184

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