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Authors

Grames, Eliza M

Noriega, Jorge A

Sanchez Herrera, Melissa

et al.

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	Wagner, David; University of Connecticut, Ecology And Evolutionary Biology Ware, Jessica; AMNH, Biology; American Museum of Natural History, Division of Invertebrate Zoology
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SCHOLARONE MANUSCRIPTS

Corresponding author: Eliza M. Grames, 4400 Vestal Parkway East, Binghamton, NY 13902, 607-777-2438, egrames@binghamton.edu

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

Eliza M. Grames[1], Jorge A. Noriega[2], Melissa Sanchez Herrera[3], Julia E. Earl[4], Elinor M. Lichtenberg[5], Marianne Alleyne[6], Kirsten M. Prior[1], Chao Guo[7], Thiago Carvalho Moretti[8], T. Caswell Munyai[9], Peter King[10], Matthew R. Pintar[11], Kayla I. Perry[12], Louie H. Yang[13], Paul Manning[14], Matthew W. Bulbert[15], Nathan L. Haan[16], Geoff M. Gurr[17], Andrew K. Jones[15], Jeff Ollerton[18,19], Todd M. Palmer[20], Göran Sahlén[21], Sebastian Seibold[22], Dominik Thom[23], Chris A. Halsch[1], Christie A. Bahlai[24], Chris S. Elphick[25], David L.Wagner[25], and Jessica L.Ware[26]

[1] Binghamton University, Binghamton, NY USA
[2] Universidad El Bosque, Bogotá, Colombia
[3] MaSuy Fundación, Bogotá, Colombia
[4] Louisiana Tech University, Ruston, LA USA
[5] University of North Texas, Denton, TX USA
[6] University of Illinois Urbana-Champaign, Urbana, IL USA
[7] Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
[8] Independent Researcher, Campinas, Brazil
[9] University of KwaZulu-Natal, Pietermaritzburg, South Africa
[10] University of Leeds, Leeds, UK
[11] Florida International University, Miami, FL USA
[12] The Ohio State University, Wooster, OH USA
[13] University of California Davis, Davis, CA USA
[14] Dalhousie University, Truro, NS Canada
[15] Oxford Brookes University, Oxford, UK
[16] University of Kentucky, Lexington, KY USA
[17] Charles Sturt University, Orange, NSW Australia
[18] University of Northampton, Northampton, UK
[19] Chinese Academy of Sciences, Kunming, China
[20] University of Florida, Gainesville, FL USA
[21] Halmstad University, Halmstad, Sweden
[22] Ulm University, Ulm, Germany
[23] Dresden University of Technology, Dresden, Germany
[24] Kent State University, Kent, OH USA
[25] University of Connecticut, Storrs, CT USA
[26] American Museum of Natural History, New York, NY USA

Abstract

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, 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 services, 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 (Garcia-Robledo et al. 2020), 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). Without insects, terrestrial and freshwater ecosystems and food webs would collapse. Plants would 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. in review) that consume insects could be negatively impacted. Global carbon cycles would 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 would 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 1-2% 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 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. (this volume).

Throughout this review, we adopt the framework used by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (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 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. in review). Bioturbation by termites also maintains earthen mounds,

115 particularly in arid environments, which serve as key grazing and burrowing sites for mammals
116 and the structure of which alters plant community composition (Sileshi et al. 2010). Ant nests are
117 often used by other species due to their stable humidity and effects on soil structure and function
118 (Fig. 1d, Folgarait 1998, Farji-Brener and Werenkraut 2017), especially in nests constructed by
119 fungus-growing ant species that are frequently used as oviposition sites by herpetofauna (Cooke
120 et al. in review). Wood-boring species also accelerate decomposition and create microhabitats in
121 wood used by invertebrates, fungi, and other taxa (Stokland et al. 2012, Ulyshen 2016).
122
123 *Plant community assembly patterns are often driven by insect activity (established but*
124 *incomplete).* When termites construct mounds, they aerate soil, enhance water filtration, and
125 concentrate nutrients, creating fertile "islands" that influence vegetation patterns (Holt and
126 Lepage 2000, Jouquet et al. 2006, Sileshi et al. 2010, Pennisi 2015). Ants likewise modify
127 landscapes through their nest building, foraging, and seed dispersal activities. They transport and
128 mix soil (Eldridge and Pickard 1994, Richards 2009), redistributing nutrients across the
129 landscape (Farji-Brener and Werenkraut 2017) and subsequently impacting plant communities.
130 Moreover, many insects play key roles in nutrient cycling, soil formation, and seed dispersal,
131 which maintain ecosystem function and structure plant community assembly dynamics (Prior et
132 al. 2020). For instance, ant-plant mutualisms can determine plant demography and vegetation
133 structure (Rosumek et al. 2009, Kamaru et al. 2024), and dung beetles improve soil structure
134 (Nichols et al. 2008, Slade et al. 2016) providing key soil resources for plant communities.
135
136 *Insects facilitate natural forest regeneration through seed dispersal and pollination (established*
137 *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 30-40% 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

161 are obligate coprophages (Hanski and Cambefort 1991) and exhibit a wide variety of physical
162 and life history traits that underpin their importance in dung removal (Wagner et al. 2021).
163 Feeding guild is an important predictor of dung removal contributions, and species that build
164 subterranean nests where broods develop within translocated dung (i.e., rollers and tunnellers)
165 generally contribute more to this ecosystem service than species that feed and brood within the
166 dung itself (i.e., dwellers) because of the processing and movement of dung (Buse and Entling
167 2020). Larger bodied species also contribute more to dung removal than smaller species.
168 Because species' traits are associated with different levels of dung removal (DeCastro-Arrazola
169 et al. 2020), changes in community composition—including the loss of functionally efficient
170 species or declines in their abundance—can result in rapid shifts in this ecosystem service
171 (Nervo et al. 2014, Manning and Cutler 2018, Milotic et al. 2018). Human activity, primarily
172 land use change and the use of veterinary parasiticides, are well established as drivers of dung
173 beetle community composition and abundance (Noriega et al. 2021), and as such dung removal is
174 an ecosystem service that is highly sensitive to anthropogenic disturbance.
175
176 *Carcass decomposition by insects is critical for dead biomass removal and nutrient cycling in*
177 *terrestrial and aquatic ecosystems (well established)*. Carrion, the decaying flesh of a deceased
178 animal, is a relatively small part of the detritus pool (Parmenter and MacMahon 2009), yet is
179 disproportionately important for ecosystem function and nutrient cycling relative to more
180 common forms of detritus like decaying plant matter (Barton et al. 2013). Large vertebrate
181 carcasses in particular can dramatically alter soil nitrogen levels in localized patches (Parmenter
182 and MacMahon 2009) affecting nutrient availability which in turn impacts on bacteria and fungi
183 (Bump et al. 2009a) and plant communities (Towne 2000, Bump et al. 2009b). Given the

184 importance of carrion decomposition to ecosystem function and structure, the role of insects in
185 decomposition is critical to both removing dead biomass from terrestrial ecosystems and
186 facilitating nutrient cycling (Fig. 1e). The majority of insects responsible for carcass
187 decomposition belong to Diptera and Coleoptera, which represent 60% of insect fauna on carrion
188 (Moretti et al. 2008), yet because carrion is extremely nutrient-rich, it attracts a wide array of
189 insects (Braack 1987, Watson 2004). These insects include necrophagous species that feed on
190 carcass tissue such as blow flies (Diptera: Calliphoridae) and flesh flies (Diptera:
191 Sarcophagidae). Unlike carrion flies, which are typically necrophagous, carrion beetles occupy
192 various niches within the decomposition food web. Many beetles are predators and parasites of
193 other insects found in carcass tissue (e.g., rove beetles, Coleoptera: Staphylinidae), omnivores
194 that capitalize on the availability of carcass tissue and the concentration of insects in a single
195 location, and adventive species that exploit carcasses as an extension of their habitat (Smith
196 1986). The order in which insects colonize decomposing carcasses is so predictable that insect
197 community composition can be used in forensic analyses (Amendt et al. 2015). By breaking
198 carcasses into smaller fragments, these same insects ensure that materials are more easily
199 processed by microorganisms, thereby being essential for energy and nutrient cycles of
200 decomposing organisms (Barton et al. 2013, Schowalter 2013).
201
202 **Pollination of flowers and dispersal of seeds**
203
204 *Insect pollination is fundamental to plant evolution (well established).* Pollination by insects is
205 an ancient ecological interaction with deep evolutionary roots (Fig. 1b). Fossil evidence indicates
206 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 80-90% of flowering plants rely on animal pollinators, the overwhelming majority of which (>90%) are insects (Ollerton et al. 2011). Recent syntheses also suggest that approximately 40% of the circa 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

253 thus increasingly recognized as a global priority for sustainable agriculture, biodiversity
254 conservation, and human health and well-being (Ollerton 2021).
255
256 *Ants, and other insects, are critical seed dispersers for many terrestrial plants (established but*
257 *incomplete).* Seed dispersal by insects (Fig. 1c) benefits plants by moving seeds away from
258 parents to high-quality microsites, enabling colonization of new areas and facilitating protection
259 from seed predators (Howe and Smallwood 1982, Schupp et al. 2010). Insects disperse seeds as
260 primary and secondary dispersers (Penn and Crist 2018). Ants are especially important insect
261 seed dispersers, as many are involved in myrmecochory – a mutualism in which seeds have
262 adaptations that entice ants which function as their primary dispersers (Bronstein et al. 2006,
263 Giladi 2006). Approximately 11,000 plant species, across diverse lineages, are myrmecochores,
264 with high concentrations of myrmecochory in shrublands of South Africa and Australia, and in
265 temperate forests in Eurasia and North America (Lengyel et al. 2010). These myrmecochores
266 produce seeds with nutrient-rich appendages called elaiosomes that ants remove after dispersing
267 seeds, leaving seeds intact either in ant nests or deposited nearby. Typically, very few ant species
268 are responsible for the vast majority of seed dispersal for myrmecochores in an ecosystem
269 (Giladi 2006, Ness et al. 2009, Warren and Giladi 2014) and this degree of specialization makes
270 plant communities sensitive to changes in ant assemblages (Rodriguez-Cabal et al. 2012, Prior et
271 al. 2015, Warren et al. 2017). For example, after invasive ants displaced native ants in the South
272 African fynbos ecosystem, the plant community shifted as well (Christian 2001). Despite feeding
273 on seeds, several seed-harvesting ants will also disperse seeds that they drop or cache, which can
274 benefit plant communities especially in desert and grassland ecosystems (Penn and Crist 2018,
275 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-Arrazole et al. 2020). More rarely, orthopterans and wasps have been observed moving seeds (Jules 1996, Gomez et al. 2018) 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 ~1×10^{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 cycling of nitrogen and carbon (Wolters 2000). The burrowing activity of arthropods creates tunnels within the soil profile, and these behaviors improve soil structure for plant growth, including porosity and water holding capacity (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) (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 10-40% 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

344 species increases wood decomposition rates directly and indirectly by altering fungal
345 communities (Zou et al. 2023), however, species identity also matters as some beetles can
346 introduce fungi that lower the overall decomposition rate (Skelton et al. 2020). Similarly, leaf
347 litter decomposition rates are strongly affected by the functional diversity of invertebrates, rather
348 than by species richness alone (Heemsbergen et al. 2004) suggesting that individual species play
349 key roles.
350
351 *Carbon release and sequestration due to insect activity have shifted as a result of global change*
352 *(established but incomplete)*. Forest disturbances caused by insects have increased dramatically
353 worldwide (Kautz et al. 2016, Miguel et al. 2026). Past increases in disturbance were driven by
354 climate change and ecosystem modifications by humans (Seidl et al. 2017). For instance, in
355 Central Europe, conifers were widely planted during the 20th century on sites that have since
356 become unsuitable for conifers under shifting climate conditions (Seidl et al. 2011). In North
357 America, trees are more susceptible to insect outbreaks due to decades of fire suppression which
358 produced dense forests with heightened resource stress (Fettig et al. 2022). Large-scale bark
359 beetle outbreaks have been increasing more rapidly than other disturbance agents such as wind or
360 fire in recent decades (Kurz et al. 2008, Hlásny et al. 2021, Kärvemo 2023, Patacca et al. 2023).
361 Insect disturbances are likely to continue increasing under climate change, potentially causing
362 fundamental shifts in tree species composition (Grünig et al. 2026). Following a bark beetle
363 disturbance, carbon sequestration is immediately reduced for several years because
364 photosynthesis is limited by foliage, however, compared to other disturbance agents, the release
365 of carbon following insect outbreaks is relatively slow (Kurz et al. 2008, Hicke et al. 2013).
366 Insect disturbances result in standing deadwood, which decomposes slowly compared to fallen

367 trees on the forest floor, and it can take years or even decades before carbon release after an
368 insect disturbance equals that after windthrows or forest fires (Fettig et al. 2022). The
369 revitalization of an ecosystem after an insect disturbance may even lead to medium- to long-term
370 increases in carbon sequestration, but the potential for carbon uptake is heavily dependent on
371 future climate scenarios, tree species composition, and forest structural characteristics (Thom et
372 al. 2022).
373
374 *Insect activities transport nutrients across habitat boundaries (well established)*. Insects
375 frequently play an important role in the movement of nutrients between terrestrial and freshwater
376 ecosystems (Nowlin et al. 2007, Gratton et al. 2008, Sato et al. 2011a, 2011b, Hoekman et al.
377 2012, Raitif et al. 2019). Emergence of aquatic insects (Fig. 2b) in particular represents a
378 substantial flux of nutrients from aquatic to terrestrial ecosystems. It is estimated that the
379 deposition of midges (Diptera: Chironomidae) near lake shores amounts to 10 kg of nitrogen per
380 hectare per year, and 1 kg of phosphorus per hectare per year (Dreyer et al. 2015). This nutrient
381 influx scales up to affect ecosystems. At lakes that have high midge abundance, shoreline plants
382 have upwards of 10% more nitrogen content than lakes with low midge abundance, and
383 caterpillars are not only more abundant but also much larger (Bultman et al. 2014) potentially
384 providing more food to insectivorous birds (Grames et al. 2023). Because many insects emerge
385 en masse, the flux of carbon and other nutrients from aquatic to terrestrial habitats represents a
386 major resource pulse (Walters et al. 2018). There is also increasing evidence that aerial
387 movements of insects at high altitudes can represent a substantial biomass transport over long
388 distances (Hu et al. 2016, Satterfield et al. 2020).
389

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 10-40% 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. 2008, 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 Merritt 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, Olafsson and Paterson 2004, Statzner 2012, Holker et al. 2015). How these ecosystem 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 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 crop production (well established). 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 2013). As a cultural practice, entomophagy reflects sustainable harvesting practices and seasonal ecological knowledge (Hlongwane et al. 2021). Harvesting edible insects

551 in cultures that practice entomophagy plays a significant role in enhancing food security
552 (Kelemu et al. 2015), generating income, and fostering social identity. These practices are
553 increasingly threatened by climate change, habitat loss, overharvesting, and changing diets,
554 which collectively erode both the insect biodiversity underpinning entomophagy, as well as
555 cultural diversity (Hlongwane et al. 2021).
556
557 *Insects are a critical alternative protein source for humans and animals (established but*
558 *incomplete)*. While entomophagy is an established practice in many cultures, in Western cultures
559 it has recently gained traction as a source of both food and animal feed. Recent studies have
560 found that insects are a source of high-quality protein, essential amino acids, polyunsaturated
561 fatty acids, vitamins, and minerals, and often have a superior nutritional yield relative to
562 environmental footprint ratio compared to conventional livestock (Anyasi et al. 2025). The
563 production of insects requires far less land, water, and feed than conventional livestock, while
564 also emitting fewer greenhouse gases, thereby contributing to climate-smart food systems and
565 circular bioeconomies (Abbasi 2025). In addition to direct human consumption, insects are
566 increasingly being used as an alternative protein source for animal feed, especially for
567 aquaculture and poultry production (Shah et al. 2022). Species such as the black soldier fly (*H.*
568 *illucens*) and yellow mealworm (*T. molitor*) can be mass-reared on organic waste streams as
569 livestock feed, while also contributing to nutrient cycling and circular bioeconomies (Ganesan et
570 al. 2024). This sector is expanding rapidly, driven by technological innovation, regulatory
571 advancements, and increasing investor interest in sustainable protein alternatives.
572

573 *Key food resources humans depend on are reliant on insects (well established)*. Insects are
574 fundamental components of terrestrial and freshwater food webs that directly and indirectly
575 support wild and free-ranging animals that humans rely on as food resources (Schoenly et al.
576 1991, Yang and Gratton 2014). Given their abundance and nutrient content, insects are prey for a
577 wide variety of organisms consumed by people via subsistence hunting and as bushmeat, such as
578 rodents (Ivanter et al. 2015), bats (Feldhamer et al. 2009), frogs (Solé and Rödder 2010), and
579 reptiles (Pough 1973). In regions with regulated hunts, insects are consumed by some of the most
580 important game birds such as ducks (Einarsson and Gardarsson 2004). Similarly, free-ranging
581 domesticated birds such as chickens opportunistically feed on insects (Coletta et al. 2012).
582 Perhaps most notably, insects comprise the majority of biomass in the diets of many freshwater
583 fishes (Grant 2001) and crayfish (Alcorlo et al. 2004), that feed on both freshwater insects and
584 terrestrial insects at the water surface. Fish that rely heavily on insects include common game
585 fish such as bass and sunfish (Sammons 2012), as well as commercially harvested species such
586 as migratory salmon which gain over half of their energy intake from insects in their juvenile
587 stages (Kawaguchi and Nakano 2001).
588
589 **Materials and assistance**
590
591 *Products derived from insects have been used by humans for centuries in textiles, dyes,*
592 *cosmetics, and crafts (well established)*. Silk is perhaps the most famous insect-derived product
593 in human history (Fig. 3b). Produced by the silkworm, (*Bombyx mori* Linnaeus, 1758), it has
594 been used by humans for well over seven thousand years (Yang et al. 2014) to produce textiles,
595 played a major role in global trade for much of human history, and continues to be used for

596 diverse purposes ranging from clothing and decor to medicine. Insects have also been used to
597 produce dyes for textiles and cosmetics (Serrano et al. 2015). Carmine, also called cochineal
598 extract, is a pigment derived from a scale insect (*Datylopius coccus* Costa 1835) used for
599 centuries as a natural, vibrant red dye. It is used in fabrics and as a food coloring, but is perhaps
600 best known for its use in cosmetics such as lipsticks and blushes (Akcay 2024). Another scale
601 insect (*Kermes vermilio* Planchon 1864) was similarly used to produce a scarlet dye for centuries
602 and is the namesake of the color vermillion. Lac, a resin derived from the lac bug (*Kerria lacca*
603 Kerr 1782), was first used as a material and red dye in India over five thousand years ago.
604 Shellac has been used throughout its history as a wax seal, food dye, a varnish for wood
605 paneling, to produce vinyl records, manufacture ballet shoes, polish violins and other string
606 instruments, and in many other diverse products, all of which depend on the lac bug (Fig. 3a,
607 Ahuja and Rastogi 2023). Beeswax similarly has had numerous uses throughout history,
608 including for candlemaking, cosmetics, and as a preservative or lubricant.
609
610 *Insect-derived materials have the potential to transform medicine (established but incomplete)*.
611 Cantharidin, derived from blister beetles (Coleoptera: Meloidae), is a known treatment for
612 *Molluscum* infections and is being studied for its anticancer mechanisms (Kok et al. 2006). Other
613 secondary metabolites derived from insects are potentially also valuable materials for modern
614 medicine and warrant further study (Anal et al. 2025). For instance, American cockroaches
615 (*Periplaneta americana* Linnaeus 1758) produce compounds that exhibit cytotoxic activity
616 against cancer cells (Luo et al. 2014), several ant species produce anti-inflammatory compounds
617 (Tang et al. 2015), a compound derived from grasshoppers induces apoptosis in leukemia cells
618 (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, as 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. 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 800+ invertebrate-derived peptides known to have 32 functional roles in immune defence (Wang et al. 2025). 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

665 complementary therapies or drug delivery facilitators (Shi et al. 2017, Sinha and Choudhury
666 2024). Common green bottle fly maggots (*Lucilia sericata* Meigen 1826) and their secretions aid
667 wound debridement and infection management (Mohd Zubir et al. 2020). Also, insect-derived
668 chitin, chitosan, and silk proteins are used to fabricate biocompatible and biodegradable
669 materials for biosensors, tissue repair, and controlled drug release, including vaccine delivery
670 (Mei et al. 2024, Lin et al. 2025). The silkworm, *B. mori*, provides high-yield production of
671 recombinant proteins for diagnostic application (Park 2025), while bioluminescent firefly
672 luciferase remains pivotal in molecular imaging and gene function studies (Thorne et al. 2010).
673
674 **Learning and inspiration**
675
676 *Innovations in engineering, materials science, and design are inspired by insects (established but*
677 *incomplete)*. The sheer diversity of insects makes them powerful models for innovation (Stork
678 2018, Eggleton 2020) and have inspired countless advances through bio-inspired design, also
679 called bioinspiration or biomimicry (Benyus 1997, Iougina 2014, Whitesides 2015). With
680 technological advancements, we can now see, fabricate, and compute at the same scale where
681 many insects exhibit their most remarkable functional adaptations. Advanced imaging tools can
682 reveal the nano- and microstructures that enable insects to stay clean (Nguyen et al. 2014, Bello
683 et al. 2024), stick to ceilings (Gorb 2007), and display brilliant colors (Seago et al. 2009, Snell-
684 Rood 2025). Precision fabrication tools enable us to recreate these structures in the lab and
685 incorporate them into innovative products (Ye et al. 2022, Zhang et al. 2022). Powerful
686 computational models facilitate simulations of individual insect interactions with other species
687 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 et al. 2022) 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,

711 pest regulation, pollination, and recreation—were valued at $57 billion USD annually two
712 decades ago (Losey and Vaughn 2006). For a single fruit—apples—in the United Kingdom,
713 insects improve crop yield and quality such that they add an estimated additional £5.7 million
714 pounds annually to production value (Garratt et al. 2014). Similarly, dung beetles could be
715 saving the livestock industry an estimated £367 million annually (Beynon et al. 2015). While
716 estimates vary tremendously depending on the ecosystem services considered, valuation
717 methods, time period, and geographic scope, there is no doubt that insects provide extremely
718 valuable ecosystem services and that declines in their abundance, biomass, and species richness
719 could have serious economic consequences.
720
721 *The economic value of agricultural ecosystem services other than pollination are less well*
722 *understood (inconclusive)*. While pollination has been the most frequently valued ecosystem
723 service (Noriega et al. 2018), insects contribute to global food production in other economically
724 quantifiable ways. For instance, insects can affect crop values by regulating pests (Naranjo et al.
725 2015). A few valuation methods have been used, including economic surplus (Letourneau et al.
726 2015, Zhang et al. 2018) and production functions (King et al. 2025), to show that increasing
727 natural enemy densities, or reducing pest pressure, can have significant economic benefits on
728 crop yields in many cereal crops (e.g., Lundin et al. 2021). Increasing the population of natural
729 enemies increases the thresholds for the economic use of pesticides in soybeans, for example
730 (Zhang and Swinton 2012). Limited empirical data on the relationships between pests and natural
731 enemy species, pests and crop yield response, and the effects of pesticide resistance, however,
732 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, this volume).

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

779 frequency and intensity of storms, though their role in this key regulating service is understudied.
780 Many more contributions of insects to earth system processes are not quantified, but can be
781 inferred from their key roles in supporting plant and animal populations whose roles in these
782 processes are well established.
783
784 If insects continue to decline in abundance and diversity, humanity will suffer from the loss of
785 provisioning services, with reductions in the global food supply and decreased food security,
786 stagnation in development of green energy, and loss of materials used in engineering, medicine,
787 and materials science. Insects provide essential pollination services to more than three-quarters
788 of crops, contributing to crop yields, maintaining genetic diversity of crops, and ensuring food
789 production to meet global food needs. Insect-based biofuels are an emerging source of renewable
790 energy that promise to have a lower carbon footprint and use far less water than other sources.
791 Insects also pollinate many of the world's biofuel plant crops. We would also lose the potential
792 future scientific and technical advancements we gain from insect-inspired design, research using
793 insects as model organisms, and from bioprospecting compounds produced by the vast diversity
794 of insect life. Insect model organisms, especially *D. melanogaster*, have been the cornerstone of
795 genetic research for decades and there is immense untapped potential for understanding genetic
796 architecture of diseases and other pressing problems in the immense diversity of insects. Their
797 diversity of form and function have inspired material scientists, engineers, and innovators to
798 develop new technologies and methods that improve human lives. The loss of insect biodiversity,
799 abundance, and biomass would have enormous consequences for humanity through reductions in
800 food security, energy, and innovation, as well as severe economic repercussions. The total value
801 of insect ecosystem services is nearly incalculable, and estimated values exceeding hundreds of

802 billions of dollars annually are likely severely underestimated given the many contributions
803 insects make to people, and the many irreplaceable roles they fill. It is imperative that
804 conservation actions be taken and policies implemented (Grames et al. this volume) to safeguard
805 the diversity of insect life and the many contributions they make to people.
806
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Figure legends

Figure 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.

Alt text: Photographs of a termite mound, bee pollinating a flower, an ant dispersing a seed, an ant colony, flies on a carcass, and a dung beetle rolling a ball of dung.

Figure 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.

Alt text: Photographs of wood boring beetle larvae, aquatic insect emergences, caddisfly larvae, stoneflies, mosquito larvae, and aphid mummies.

Figure 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.

Alt text: Photographs of a vinyl record, silk spools, a needle and vials, a fruit fly, insects sold at a market, and black soldier fly larvae.

Figure 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).

Alt text: a heatmap graph listing insect ecosystem services color coded by the level of scientific agreement.

Figure 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.

Alt text: A scale ranging from ecocentric at the top associated with contributions to people, to anthropocentric at the bottom associated with human quality of life, and photographs showing a bee pollinating a quince flower, a mayfly, a mosquito, a vendor of insects, a decorative butterfly, and a medieval piece of art.

Corresponding author: Eliza M. Grames, 4400 Vestal Parkway East, Binghamton, NY 13902, 607-777-2438, egrames@binghamton.edu

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

Eliza M. Grames[1], Jorge A. Noriega[2], Melissa Sanchez Herrera[3], Julia E. Earl[4], Elinor M. Lichtenberg[5], Marianne Alleyne[6], Kirsten M. Prior[1], Chao Guo[7], Thiago Carvalho Moretti[8], T. Caswell Munyai[9], Peter King[10], Matthew R. Pintar[11], Kayla I. Perry[12], Louie H. Yang[13], Paul Manning[14], Matthew W. Bulbert[15], Nathan L.e Haan[16], Geoff M. Gurr[17], Andrew K. Jones[15], Jeff Ollerton[18,19], Todd M. Palmer[20], Göeran Sahléen[21], Sebastian Seibold[22], Dominik Thom[23], Chris A. Halsch[1], Christie A. Bahlai[24], Chris S. Elphick[25], David L.e Wagner[25], and Jessica L.Ware[26]

[1] Binghamton University, Binghamton, NY USA
[2] Universidad El Bosque, Bogotá, Colombia
[3] MaSuy Fundación, Bogotá, Colombia
[4] Louisiana Tech University, Ruston, LA USA
[5] University of North Texas, Denton, TX USA
[6] University of Illinois Urbana-Champaign, Urbana, IL USA
[7] Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
[8] Independent Researcher, Campinas, Brazil
[9] University of KwaZulu-Natal, Pietermaritzburg, South Africa
[10] University of Leeds, Leeds, UK
[11] Florida International University, Miami, FL USA
[12] The Ohio State University, Wooster, OH USA
[13] University of California Davis, Davis, CA USA
[14] Dalhousie University, Truro, NS Canada
[15] Oxford Brookes University, Oxford, UK
[16] University of Kentucky, Lexington, KY USA
[17] Charles Sturt University, Orange, NSW Australia
[18] University of Northampton, Northampton, UK
[19] Chinese Academy of Sciences, Kunming, China
[20] University of Florida, Gainesville, FL USA
[21] Halmstad University, Halmstad, Sweden
[22] Ulm University, Ulm, Germany
[23] Dresden University of Technology, Dresden, Germany
[24] Kent State University, Kent, OH USA
[25] University of Connecticut, Storrs, CT USA
[26] American Museum of Natural History, New York, NY USA

Abstract

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 ~~and provide services that contribute to ecosystem function and planetary~~

~~processes~~. 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, 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. ~~could have devastating consequences for ecosystem function, food security, energy, innovation, and scientific advancement, with economic impacts overshadowed by the loss of services so central to all life that their value is incalculable.~~

Keywords: ecosystem services, 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 (Garcia-Robledo et al. 2020), 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). Without insects, terrestrial and freshwater ecosystems and food webs would collapse. Plants would 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. in review) that consume insects could be negatively impacted. Global carbon cycles would 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 would 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 1-2% 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 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~~, and decontamination of soils~~), 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. (this volume).

Throughout this review, we adopt the framework used by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (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 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. in review). Bioturbation by termites also maintains earthen mounds,

119 particularly in arid environments, which serve as key grazing and burrowing sites for mammals
120 and the structure of which alters plant community composition (Sileshi et al. 2010). Ant nests are
121 often used by other species due to their stable humidity and effects on soil structure and function
122 (Fig. 1d, Folgarait 1998, Farji-Brener and Werenkraut 2017), especially in nests constructed by
123 fungus-growing ant species that are frequently used as oviposition sites by herpetofauna (Cooke
124 et al. in review). Wood-boring species also accelerate decomposition and create microhabitats in
125 wood used by invertebrates, fungi, and other taxa (Stokland et al. 2012, Ulyshen 2016).
126
127 *Plant community assembly patterns are often driven by insect activity (established but*
128 *incomplete).* When termites construct mounds, they aerate soil, enhance water filtration, and
129 concentrate nutrients, creating fertile "islands" that influence vegetation patterns (Holt and
130 Lepage 2000, Jouquet et al. 2006, Sileshi et al. 2010, Pennisi 2015). Ants likewise modify
131 landscapes through their nest building, foraging, and seed dispersal activities. They transport and
132 mix soil (Eldridge and Pickard 1994, Richards 2009), redistributing nutrients across the
133 landscape (Farji-Brener and Werenkraut 2017) and subsequently impacting plant communities.
134 Moreover, many insects play key roles in nutrient cycling, soil formation, and seed dispersal,
135 which maintain ecosystem function and structure plant community assembly dynamics (Prior et
136 al. 2020). For instance, ant-plant mutualisms can determine plant demography and vegetation
137 structure (Rosumek et al. 2009, Kamaru et al. 2024), and dung beetles improve soil structure
138 (Nichols et al. 2008, Slade et al. 2016) providing key soil resources for plant communities.
139
140 *Insects facilitate natural forest regeneration through seed dispersal and pollination (established*
141 *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 30-40% 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

165 are obligate coprophages (Hanski and Cambefort 1991) and exhibit a wide variety of physical
166 and life history traits that underpin their importance in dung removal (Wagner et al. 2021).
167 Feeding guild is an important predictor of dung removal contributions, and species that build
168 subterranean nests where broods develop within translocated dung (i.e., rollers and tunnellers)
169 generally contribute more to this ecosystem service than species that feed and brood within the
170 dung itself (i.e., dwellers) because of the processing and movement of dung (Buse and Entling
171 2020). Larger bodied species also contribute more to dung removal than smaller species.
172 Because species' traits are associated with different levels of dung removal (DeCastro-Arrazola
173 et al. 2020), changes in community composition—including the loss of functionally efficient
174 species or declines in their abundance—can result in rapid shifts in this ecosystem service
175 (Nervo et al. 2014, Manning and Cutler 2018, Milotic et al. 2018). Human activity, primarily
176 land use change and the use of veterinary parasiticides, are well established as drivers of dung
177 beetle community composition and abundance (Noriega et al. 2021), and as such dung removal is
178 an ecosystem service that is highly sensitive to anthropogenic disturbance.
179
180 *Carcass decomposition by insects is critical for dead biomass removal and nutrient cycling in*
181 *terrestrial and aquatic ecosystems (well established)*. Carrion, the decaying flesh of a deceased
182 animal, is a relatively small part of the detritus pool (Parmenter and MacMahon 2009), yet is
183 disproportionately important for ecosystem function and nutrient cycling relative to more
184 common forms of detritus like decaying plant matter (Barton et al. 2013). Large vertebrate
185 carcasses in particular can dramatically alter soil nitrogen levels in localized patches (Parmenter
186 and MacMahon 2009) affecting nutrient availability which in turn impacts on bacteria and fungi
187 (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 80-90% of flowering plants rely on animal pollinators, the overwhelming majority of which (>90%) are insects (Ollerton et al. 2011). Recent syntheses also suggest that approximately 40% of the circa 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 ~~storage, and~~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 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). Insects disperse seeds as primary and secondary dispersers (Penn and Crist 2018). Ants are especially important insect seed dispersers, 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. 2012, 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-Arrazole et al. 2020). More rarely, orthopterans and wasps have been observed moving seeds (Jules 1996, Gomez et al. 2018) 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 ~1×10^{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 cycling of nitrogen and carbon (Wolters 2000). The burrowing activity of arthropods creates tunnels within the soil profile, and these behaviors improve soil structure for plant growth, including porosity and water holding capacity (Lee and Foster 1991). Termites (Blattodea: Isoptera), ants (Hymenoptera: Formicidae), and dung beetles

303 (Coleoptera: Scarabaeidae) have substantial impacts on the physical, chemical, and biological
304 properties of soil due to their roles as ecosystem engineers (Folgarait 1998, Bang et al. 2005,
305 Jouquet et al. 2006). Some species of ants and termites maintain subterranean colonies. The
306 creation and maintenance of these nests mix soil layers, reduce soil compaction, increase
307 porosity and water holding capacity, and improve water infiltration into the soil (Fig. 1d, Lobry
308 de Bruyn and Conacher 1990, Frouz and Jilkova 2008, Govorushko 2019).
309
310 *Insects are useful indicators of soil contamination and assessment of remediation, but their role*
311 *in bioremediation is underused* (established but incomplete). Insects are commonly used as
312 bioindicators of contamination from anthropogenic activities such as development, industry, and
313 agriculture because of their critical roles in soil structure and function, including decomposition
314 and nutrient cycling, and their importance in soil food webs (Santorufo et al. 2012, Nsengimana
315 et al. 2018). Their roles in bioremediation of contaminated or degraded soils have received less
316 attention, but recent research highlights the potential for entomoremediation by ecosystem
317 engineers (e.g., ants, termites, dung beetles) (Hefft et al. 2022), ground beetles (Tőzsér et al.
318 2019), black soldier fly (*Hermetia illucens* Linneaus 1758; Diptera: Stratiomyidae) larvae
319 (Raksasat et al. 2020, Bulak et al. 2021), larvae of *Propsilocerus akamusi* (Tokunaga) (Diptera:
320 Chironomidae) (Zheng et al. 2024), and larvae of the mealworm (*Tenebrio molitor* Linneaus
321 1758) (Coleoptera: Tenebrionidae) (Bulak et al. 2021). This process of entomoremediation relies
322 on the ability of these insects to either bioaccumulate and sequester contaminants within their
323 body tissues or biotransform the compounds through digestive enzymes and associated
324 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 (~~established but incomplete~~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 10-40% 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. 2016, Miguel et al. 2026). Past increases in disturbance were driven by ~~as a result of~~ 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 2023, Patacca et al. 2023). Insect disturbances are ~~also~~ likely to continue increasing ~~in frequency~~ under climate change, potentially causing fundamental shifts ~~until a tipping point~~ in tree species composition ~~is reached~~ (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 (~~Patacca et al. 2023~~Kurz et al. 2008, Hicke et al. 2013). Insect disturbances result

371 in standing deadwood, which decomposes slowly compared to fallen trees on the forest floor,
372 and it can take years or even decades before ~~rates of~~ carbon release after an insect disturbance
373 equals that after ~~approach those of~~ windthrows or forest fires (Fettig et al. 2022). The
374 revitalization of an ecosystem after an insect disturbance may even lead to medium- to long-term
375 increases in carbon sequestration, but the potential for ~~sequestration~~ carbon uptake is heavily
376 dependent on future climate scenarios, tree species composition, and forest structural
377 characteristics (Thom et al. 2022).
378
379 *Insect activities transport nutrients across habitat boundaries (well established)*. Insects
380 frequently play an important role in the movement of nutrients between terrestrial and freshwater
381 ecosystems (Nowlin et al. 2007, Gratton et al. 2008, Sato et al. 2011a, 2011b, Hoekman et al.
382 2012, Raitif et al. 2019). Emergence of aquatic insects (Fig. 2b) in particular represents a
383 substantial flux of nutrients from aquatic to terrestrial ecosystems. It is estimated that the
384 deposition of midges (Diptera: Chironomidae) near lake shores amounts to 10 kg of nitrogen per
385 hectare per year, and 1 kg of phosphorus per hectare per year (Dreyer et al. 2015). This nutrient
386 influx scales up to affect ecosystems. At lakes that have high midge abundance, shoreline plants
387 have upwards of 10% more nitrogen content than lakes with low midge abundance, and
388 caterpillars are not only more abundant but also much larger (Bultman et al. 2014) potentially
389 providing more food to insectivorous birds (Grames et al. 2023). Because many insects emerge
390 en masse, the flux of carbon and other nutrients from aquatic to terrestrial habitats represents a
391 major resource pulse (Walters et al. 2018). There is also increasing evidence that aerial
392 movements of insects at high altitudes can represent a substantial biomass transport over long
393 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 (~~established but incomplete~~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 10-40% 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.

417

418 **Regulation of freshwater quality**

419

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

438

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. 2008, 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 Merritt 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).

461 *Insects may reduce plastic pollution in freshwater ecosystems (inconclusive*). Preliminary
462 evidence suggests that aquatic insect processing of materials may help break down and export
463 microplastics from freshwater ecosystems (Drummond et al. 2025, Ma et al. 2025). This is an
464 emerging field of research and the general impacts of insects on plastic pollution remediation are
465 unclear.
466
467 **Regulation of hazards and extreme events**
468
469 *Aquatic insects promote ecosystem resilience to storms (inconclusive)*. Insects increase substrate
470 stability in freshwater ecosystems. Net spinning caddisfly and black fly larvae connect substrate
471 sediment particles with their silk, which reduces suspended solids in streams (Fig. 2c) under
472 ambient conditions and during storm events (Adler and Courtney 2019, Morse et al. 2019). Silk
473 tubes created by non-biting midge larvae also stabilize lake sediments (Edwards 1962, Olafsson
474 and Paterson 2004, Statzner 2012, Holker et al. 2015). How these ecosystem functions scale up
475 to ecosystem resilience under increasing frequency and severity of storms under climate change
476 is unclear.
477
478 **Regulation of organisms detrimental to humans**
479
480 *Predatory and parasitoid insects are important contributors to agricultural and forest pest*
481 *management (well established)*. Many insects are 'natural enemies' that exert top down trophic
482 pressure on pest populations via direct predation or parasitism thereby regulating pest abundance
483 (Fig. 2f). A meta-analysis of the effects of biological control to increase predatory and parasitoid

484 insects found overall positive effects on crop yield, reductions in crop damage, and decreases in
485 pest abundance (Ratto et al. 2022). These 'natural enemies' often respond favorably to increased
486 landscape complexity (Chaplin-Kramer et al. 2011, Shackelford et al. 2013) More recently, non-
487 consumptive effects of natural enemies on pest populations have been documented, such as
488 disrupting feeding activities that alleviates negative impacts on crop yields even with no change
489 in the abundance of the pest population (Ali et al. 2025). Actions that positively affect natural
490 enemies result in greater benefits from this ecosystem service, though results depend on the
491 landscape context (Karp et al. 2018, Crowther et al. 2023). This service can be particularly
492 important in regions where pesticides are unavailable or too expensive, especially for
493 smallholder farms.
494
495 *Aquatic insects regulate disease vector populations (established but incomplete)*. Many aquatic
496 insects, particularly Odonata (dragonflies and damselflies), are predators of disease vectors such
497 as mosquito larvae (Fig. 2e, Shaalan and Canyon 2009). While Odonata are the most highly
498 effective at regulating populations of disease vectors (Priyadarshana and Slade 2023), insects
499 from many orders function as vector control, separately, or in combination with, other taxa
500 (Staats et al. 2016). Most evidence on the effectiveness of insects at controlling disease vectors
501 comes from lab trials which may not accurately reflect prey preferences in nature, as many
502 potential predators of disease vectors are polyphagous (Shaalan and Canyon 2009), however,
503 results indicate that insects are capable of controlling vector population in lab settings. Full scale
504 ventures to suppress mosquito larvae through the use of insects as vector control have also been
505 implemented in urban settings from Myanmar (Sebastian et al. 1990) to the United States
506 (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 crop production (well established). 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 ~~less~~ 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 2013). As a cultural practice, entomophagy reflects sustainable harvesting practices and seasonal ecological knowledge (Hlongwane et al. 2021). 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. 2021).

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

598 in human history (Fig. 3b). Produced by the silkworm, (*Bombyx mori* Linnaeus, 1758), it has
599 been used by humans for well over seven thousand years (Yang et al. 2014) to produce textiles,
600 played a major role in global trade for much of human history, and continues to be used for
601 diverse purposes ranging from clothing and decor to medicine. Insects have also been used to
602 produce dyes for textiles and cosmetics (Serrano et al. 2015). Carmine, also called cochineal
603 extract, is a pigment derived from a scale insect (*Datylopius coccus* Costa 1835) used for
604 centuries as a natural, vibrant red dye. It is used in fabrics and as a food coloring, but is perhaps
605 best known for its use in cosmetics such as lipsticks and blushes (Akcay 2024). Another scale
606 insect (*Kermes vermilio* Planchon 1864) was similarly used to produce a scarlet dye for centuries
607 and is the namesake of the color vermillion. Lac, a resin derived from the lac bug (*Kerria lacca*
608 Kerr 1782), was first used as a material and red dye in India over five thousand years ago.
609 Shellac has been used throughout its history as a wax seal, food dye, a varnish for wood
610 paneling, to produce vinyl records, manufacture ballet shoes, polish violins and other string
611 instruments, and in many other diverse products, all of which depend on the lac bug (Fig. 3a,
612 Ahuja and Rastogi 2023). Beeswax similarly has had numerous uses throughout history,
613 including for candlemaking, cosmetics, and as a preservative or lubricant.
614
615 *Insect-derived materials have the potential to transform medicine (established but incomplete)*.
616 Cantharidin, derived from blister beetles (Coleoptera: Meloidae), is a known treatment for
617 *Molluscum* infections and is being studied for its anticancer mechanisms (Kok et al. 2006). Other
618 secondary metabolites derived from insects are potentially also valuable materials for modern
619 medicine and warrant further study (Anal et al. 2025). For instance, American cockroaches
620 (*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).

644 *Thousands of compounds derived from insects are used in traditional and modern medicine*
645 *(established but incomplete)*. Folkloric and modern medicine indicate hundreds of insect species,
646 from more than 15 orders, as sources of preventive and therapeutic agents (Siddiqui et al. 2023).
647 Insect cell lines are capable of producing complex proteins that are otherwise difficult to
648 synthesize, making them extremely useful for generating protein-based vaccines and therapeutic
649 agents. Insect-derived compounds enhance immunity, improve gastro-, neuro-, and cardio-
650 protection, regulate metabolism, promote tissue regeneration, and provide anti-inflammatory,
651 antitumor, and antimicrobial effects (Tanga and Ekesi 2024, Ishara et al. 2025). Moreover, their
652 microbial symbionts—bacteria, fungi, and actinomycetes—produce distinctive bioactive
653 metabolites with complementary therapeutic potential (Baranova et al. 2022, Fan et al. 2025).
654 The chemical diversity of these bioactives is equally impressive (Teixeira et al. 2023, Ishara et
655 al. 2025). The Antimicrobial Peptide Database lists 800+ invertebrate-derived peptides known to
656 have 32 functional roles in immune defence (Wang et al. 2025). Such peptides are inspiring next-
657 generation antibiotics targeting multidrug-resistant pathogens, including ESKAPE bacteria - a
658 persistent global health threat (Sahoo et al. 2021). Insect-derived peptides with potent
659 antimicrobial activity are being explored as novel therapeutics that could curb antimicrobial
660 resistance (Mylonakis et al. 2016, Manniello et al. 2021). Venom-derived peptides from bees and
661 wasps (Fratini et al. 2017, Laurindo et al. 2024, Bhardwaj et al. 2025), and cantharidin from
662 blister beetles (Zhang et al. 2025) exhibit potent anticancer properties. Honey, alone, from both
663 honey bees and stingless bees, has over 200 bioactive compounds with wide-ranging medicinal
664 applications (Hossain et al. 2021, Yupanqui Mieles et al. 2022, Palma-Morales et al. 2023,
665 Azman et al. 2024, Cabezas-Mera et al. 2024).
666

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). Also, 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, Iougina 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. 2024), 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

690 incorporate them into innovative products (Ye et al. 2022, Zhang et al. 2022). Powerful
691 computational models facilitate simulations of individual insect interactions with other species
692 and their environment, spanning from genomes, to brains, to microhabitats, and even global
693 scales (Barron et al. 2015). By studying how insects work, we can create smarter, multifunctional
694 materials, more efficient mechanical systems, and other technologies that are as resilient and
695 adaptable as insects (Wijerathne et al. 2022, March-Pons et al. 2024, Jovchevska et al. 2025,
696 Couzin 2025). Insects are mentors for innovation (Schroeder et al. 2018) from the powerful
697 spring-loaded jump of click beetles (Ribak and Weihs 2011, Bolmin et al. 2021) to the water-
698 repelling and antimicrobial wings of cicadas (Oh et al. 2017, Watson et al. 2017, Bello et al.
699 2022) and the collective intelligence of honey bees (Britton et al. 2002). With sequencing of
700 additional insect genomes in recent decades (Cameron 2025), there is an increasing number of
701 species with a broader range of traits available to support technological advancements.
702
703 **Economic valuation of ecosystem services provided by insects**
704
705 *Ecosystem services provided by insects to food production are valued at billions of USD*
706 *annually (established but incomplete)*. Given the vast diversity of functional roles insects fill and
707 their numerous contributions to people, the total value of the ecosystem services insects provide
708 is inestimable. Yet, estimates for even just a handful of services, often limited to some parts of
709 the world, place the total value of insects' contributions in the billions, if not trillions, of dollars
710 annually. Pollination is the most widely studied service provided by insects from an economic
711 perspective (Potts et al. 2016, Noriega et al. 2018) as there are a range of models to estimate the
712 economic value of pollination (Breeze et al. 2016). The value of insect pollination globally was

713 estimated at €153 billion in 2009 (Gallai et al. 2009). More recently, insect pollination services
714 in Latin America were valued at an estimated $22.95 billion USD per year (Basualdo et al.
715 2022). In the United States alone, four ecosystem services provided by insects—dung removal,
716 pest regulation, pollination, and recreation—were valued at $57 billion USD annually two
717 decades ago (Losey and Vaughn 2006). For a single fruit—apples—in the United Kingdom,
718 insects improve crop yield and quality such that they add an estimated additional £5.7 million
719 pounds annually to production value (Garratt et al. 2014). Similarly, dung beetles could be
720 saving the livestock industry an estimated £367 million annually (Beynon et al. 2015). While
721 estimates vary tremendously depending on the ecosystem services considered, valuation
722 methods, time period, and geographic scope, there is no doubt that insects provide extremely
723 valuable ecosystem services and that declines in their abundance, biomass, and species richness
724 could have serious economic consequences.
725
726 *The economic value of agricultural ecosystem services other than pollination are less well*
727 *understood (inconclusive)*. While pollination has been the most frequently valued ecosystem
728 service (Noriega et al. 2018), insects contribute to global food production in other economically
729 quantifiable ways. For instance, insects can affect crop values by regulating pests (Naranjo et al.
730 2015). A few valuation methods have been used, including economic surplus (Letourneau et al.
731 2015, Zhang et al. 2018) and production functions (King et al. 2025), to show that increasing
732 natural enemy densities, or reducing pest pressure, can have significant economic benefits on
733 crop yields in many cereal crops (e.g., Lundin et al. 2021). Increasing the population of natural
734 enemies increases the thresholds for the economic use of pesticides in soybeans, for example
735 (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, ~~butterflies~~beetles, and wasps, though this value may be conflated with pollination and is taxonomically ~~and spatially~~ biased (King et al~~. in review~~. 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, this volume).

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

781 the water column. Many insects are also sensitive to changes in water quality, and serve as
782 bioindicators used by governments around the world to track the status and trends in freshwater
783 quality. By modifying soil and serving as pollinators and seed dispersers for terrestrial plants,
784 insects may even contribute to ecosystem resilience and stability in the face of increasing
785 frequency and intensity of storms, though their role in this key regulating service is understudied.
786 Many more contributions of insects to earth system processes are not quantified, but can be
787 inferred from their key roles in supporting plant and animal populations whose roles in these
788 processes are well established.
789
790 If insects continue to decline in abundance and diversity, humanity will suffer from the loss of
791 provisioning services, with reductions in the global food supply and decreased food security,
792 stagnation in development of green energy, and loss of materials used in engineering, medicine,
793 and materials science. Insects provide essential pollination services to more than three-quarters
794 of crops, contributing to crop yields, maintaining genetic diversity of crops, and ensuring food
795 production to meet global food needs. Insect-based biofuels are an emerging source of renewable
796 energy that promise to have a lower carbon footprint and use far less water than other sources.
797 Insects also pollinate many of the world's biofuel plant crops. We would also lose the potential
798 future scientific and technical advancements we gain from insect-inspired design, research using
799 insects as model organisms, and from bioprospecting compounds produced by the vast diversity
800 of insect life. Insect model organisms, especially *D. melanogaster*, have been the cornerstone of
801 genetic research for decades and there is immense untapped potential for understanding genetic
802 architecture of diseases and other pressing problems in the immense diversity of insects. Their
803 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 (Grames et al. this volume) to safeguard the diversity of insect life and the many contributions they make to people.

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Figure legends

Figure 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.

Alt text: Photographs of a termite mound, bee pollinating a flower, an ant dispersing a seed, an ant colony, flies on a carcass, and a dung beetle rolling a ball of dung.

Figure 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.

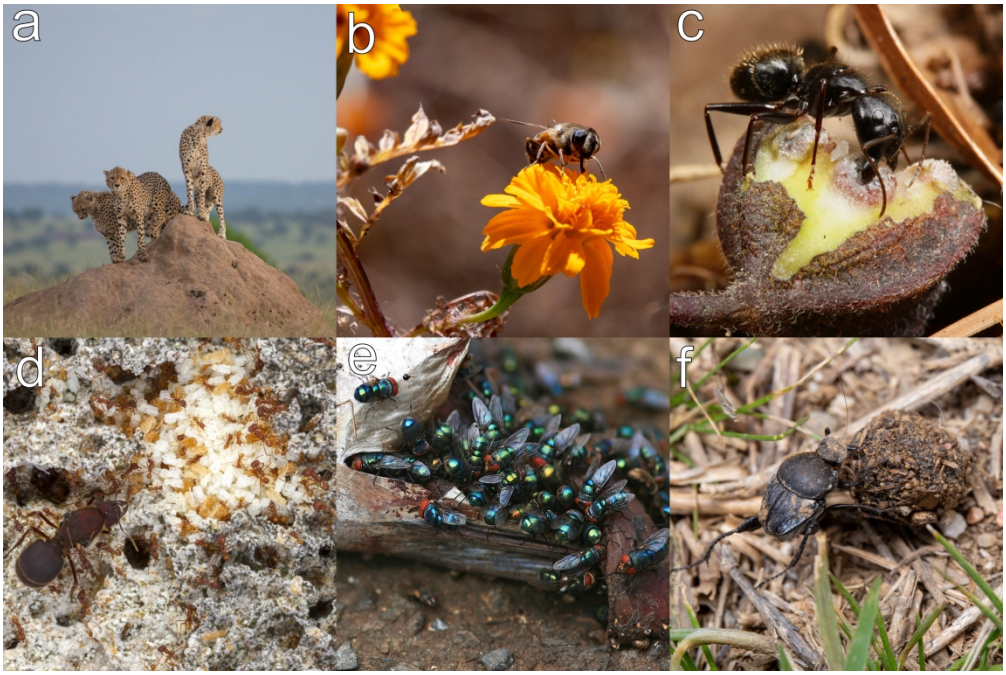
Alt text: Photographs of wood boring beetle larvae, aquatic insect emergences, caddisfly larvae, stoneflies, mosquito larvae, and aphid mummies.

Figure 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.

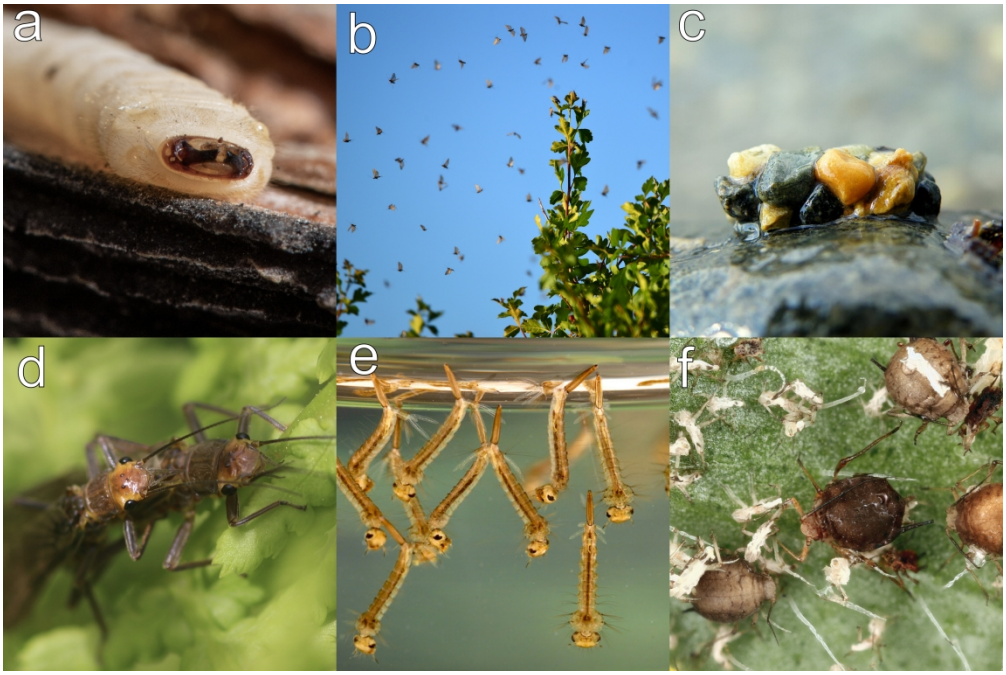
Alt text: Photographs of a vinyl record, silk spools, a needle and vials, a fruit fly, insects sold at a market, and black soldier fly larvae.

Figure 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.

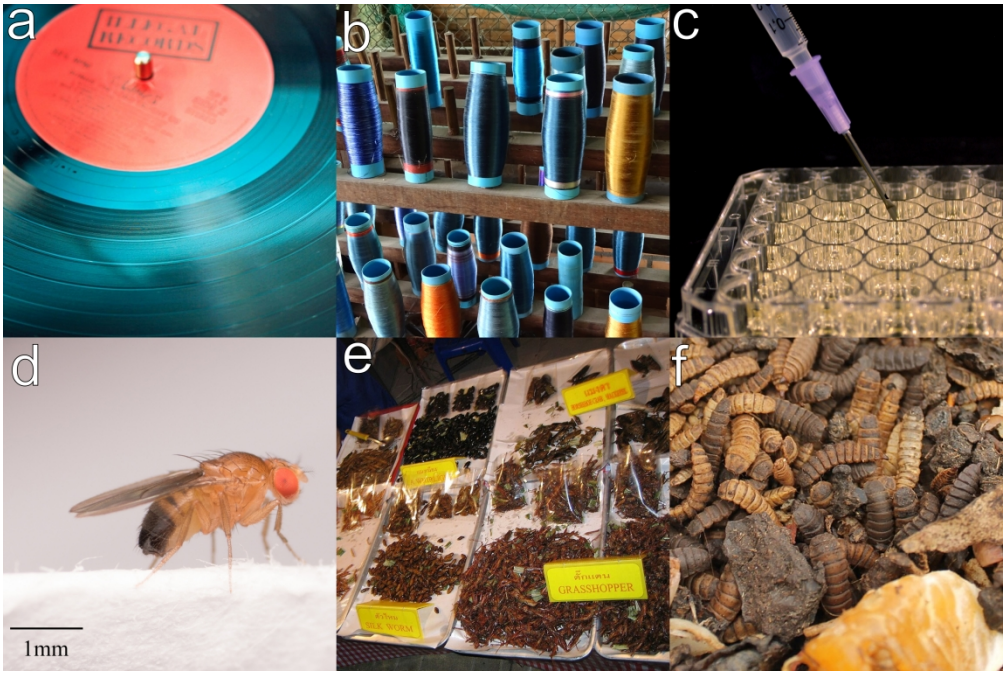
1711 Contributions are colored according to the level of confidence in the evidence, depending on if
1712 they are well established (teal), established but incomplete (mint), unresolved (yellow), or
1713 inconclusive (gray).
1714
1715 Alt text: a heatmap graph listing insect ecosystem services color coded by the level of scientific
1716 agreement.
1717
1718 Figure 5. Insects provide many ecosystem services, valued for their ecocentric contributions to
1719 people, that in turn support human quality of life, characterized by a more anthropocentric value
1720 system. For instance, a) insects pollinate many wild plants and also agricultural crops like
1721 quince, b) aquatic insect emergence represents a massive flux of energy among ecosystems that
1722 is important for ecosystem function, and also regulate c) disease vectors by consuming mosquito
1723 larvae, contributing to human quality of life by supporting public health. Insects like termites and
1724 grasshoppers are essential for habitat creation, soil formation, and nutrient cycling, and d) are
1725 also frequently consumed and support human livelihoods. Bees and butterflies serve as
1726 pollinators, and also inspire cultural identity and a sense of place such as e) in celebrations of Dia
1727 de Los Muertos and f) illustrations that adorn honey bee hives in Europe.
1728
1729 Alt text: A scale ranging from ecocentric at the top associated with contributions to people, to
1730 anthropocentric at the bottom associated with human quality of life, and photographs showing a
1731 bee pollinating a quince flower, a mayfly, a mosquito, a vendor of insects, a decorative butterfly,
1732 and a medieval piece of art.
1733



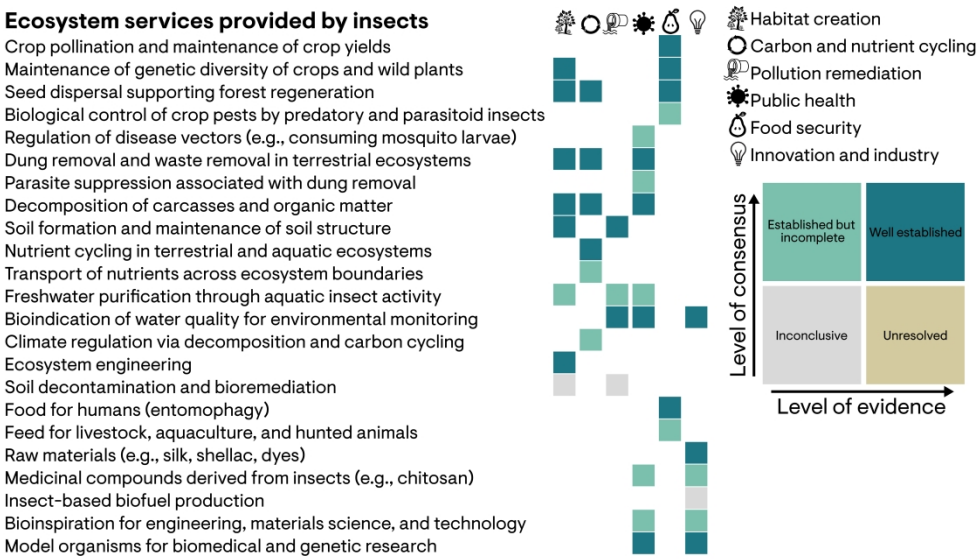
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