JSIANE : Vol. 1, Issue 2, 2021 Page 36- 40 ISSN (Online): 2583-2093

Journal of Science Innovations and Nature of Earth

Journal homepage : www.jsiane.com

Role of Insects in Nutrient Cycling and Ecosystem Services

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https://doi.org/10.59436/jsiane.v1i2.09

Abstract

Insects occupy nearly every terrestrial and freshwater habitat on earth, and their collective influence on nutrient cycling and ecosystem function is enormous. Yet much of the scientific and public conversation about insects fixates on their roles as pests or pollinators, overlooking the less visible but arguably more consequential work they do below the soil surface and within decomposing organic matter. This review synthesizes current understanding of insect-mediated nutrient cycling, covering decomposition, dung burial, bioturbation, and the broader suite of ecosystem services insects provide. Drawing on field studies, meta-analyses, and economic valuation research published through 2021, the paper examines how different functional groups of insects contribute to nitrogen and phosphorus turnover, soil structure, pest regulation, and pollination. Attention is also given to the well-documented decline in insect populations worldwide and the cascading consequences these losses may carry for ecosystem stability. The central argument here is straightforward: without insects, terrestrial nutrient cycles would slow dramatically, and the economic costs of replacing the services they provide for free would be staggering.

Keywords: Nutrient Cycling, Ecosystem Services, Entomology, Decomposition, Pollination, Soil Ecology, Biodiversity Conservation

Received 27.04.2021 Revised 16.05.2021 Accepted 20.05.2021

Introduction

Among the more than one million described species of insects, only a fraction receive sustained scientific attention, and an even smaller fraction capture public interest. Mosquitoes and honeybees get most of the headlines. But the bulk of insect biodiversity works in relative obscurity, breaking down dead wood, processing animal waste, aerating soil, and transferring nutrients from one compartment of the ecosystem to another. The collective effect of this labor is difficult to overstate. Estimates suggest that insects process between 30 and 80 percent of above-ground litter in tropical forests (Bignell and Eggleton, 2000), and in temperate grasslands, dung beetles alone can bury enough cattle dung to measurably improve pasture nitrogen availability (Nichols *et al*., 2008).

The study of insect-mediated ecosystem services has gained momentum over the past two decades, driven partly by the alarming reports of insect population declines. Hallmann *et al*. (2017) documented a 76% reduction in flying insect biomass across 63 nature reserves in Germany over a 27-year period, a finding that prompted both scientific scrutiny and broader public concern. Subsequent studies from Puerto Rico, Denmark, the Netherlands, and elsewhere have corroborated the trend, though with varying magnitudes and not always with clear causal explanations (Lister and Garcia, 2018; Wagner, 2020). Whatever the causes, the functional consequences of losing so many insects are potentially severe: decomposition slows, nutrient turnover stalls, and the organisms that depend on insects for food begin to decline in turn.

This review paper attempts to lay out the specific mechanisms by which insects participate in nutrient cycling and to assess the economic and ecological value of the ecosystem services they deliver. The goal is not simply to catalog insect contributions but to connect the ecological processes to their measurable outcomes in ways that matter for conservation planning and land management. Five figures are included to illustrate central data and relationships.

2. Insects and Soil Nutrient Cycling

Soil nutrient cycling is the process by which organic compounds are broken down into inorganic forms that plants can absorb. Bacteria and fungi carry out the final steps of mineralization, but insects often initiate and accelerate the process by physically fragmenting organic material, increasing the surface area available for microbial colonization. This is not a minor contribution. In tropical ecosystems, termites alone can process more than 50% of dead wood and leaf litter (Bignell and Eggleton, 2000), and their gut microbiomes add a biochemical dimension to what might otherwise be a purely mechanical process.

Figure 1. Insect-Mediated Nutrient Cycling in Terrestrial Ecosystems

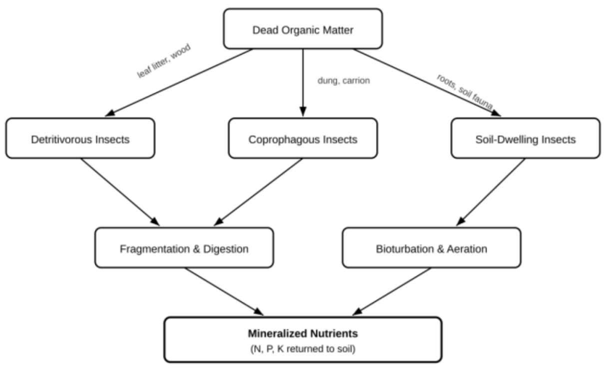


Figure 1 illustrates the general pathways through which insects mediate nutrient flows in terrestrial systems. The three main functional routes are detritivory (processing of dead plant material), coprophagy (processing of animal dung), and bioturbation (physical mixing and aeration of soil). Each route involves different insect orders, and in practice, the boundaries between them overlap. Ants, for instance, are detritivores and soil engineers simultaneously.

2.1 Detritivorous Insects and Litter Breakdown

Leaf litter decomposition in forests proceeds through a predictable sequence. Fresh leaves fall, and within days to weeks, they are colonized by fungi and bacteria. Insects enter the picture at multiple stages, but their most consequential role is in the early and middle phases, when they fragment the litter into smaller pieces and redistribute it through the upper soil layers. Termites (Isoptera) are the dominant detritivores in tropical and subtropical regions, where their colonies can extend several meters into the ground and process plant material at rates that dwarf other soil invertebrates.

In temperate forests, beetle larvae (Coleoptera), particularly those of the families Scarabaeidae and Lucanidae, take over much of the wood-decomposition work that termites perform in the tropics. Dipteran larvae also contribute, especially in moist litter layers where fly species such as Sciaridae and Mycetophilidae feed on fungal-colonized organic matter. The combined activity of these groups has been estimated to accelerate litter mass loss by 20 to 60 percent compared with microbial decomposition alone (Hattenschwiler *et al*., 2005; Frouz, 2018).

Figure 2. Estimated Contribution of Insect Orders to Litter Decomposition
(Compiled from multiple studies; approximate global averages)

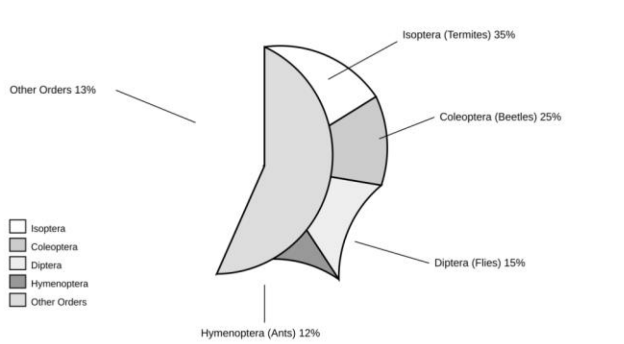


Figure 2 presents approximate global contributions of major insect orders to litter decomposition. The dominance of termites is evident, accounting for an estimated 35% of insect-mediated decomposition worldwide. Beetles follow at about 25%, with flies, ants, and a mixed category of other orders making up the remainder. These proportions shift substantially across biomes: in boreal forests, beetles and flies predominate, while in savannas, termite contributions can exceed 60% (Jouquet *et al*., 2011).

2.2 Dung Beetles and Coprophagous Insects

Dung beetles (Scarabaeidae: Scarabaeinae) receive comparatively less popular attention than pollinators, which is unfortunate given the scale of what they accomplish. A single dung beetle can bury several times its own body weight in dung per day, and in regions with active beetle communities, a fresh cow pat can be entirely removed from the pasture surface within 48 hours (Nichols *et al*., 2008). The buried dung brings nitrogen, phosphorus, and organic carbon directly into the root zone, where it becomes available to plants far more quickly than if it remained on the surface.

The economic significance of dung burial has been quantified in several studies. Losey and Vaughan (2006) estimated the value of dung burial by insects in the United States alone at approximately $380 million per year in terms of forage improvement and reduced nitrogen runoff. When you consider that the alternative to beetle-mediated dung removal is mechanical spreading or chemical treatment, both of which require fuel, labor, and equipment, the numbers become harder to dismiss. In Australia, the introduction of African dung beetle species in the 1960s and 1970s was explicitly motivated by the failure of native beetles to process cattle dung, which had become a serious pasture management problem (Bornemissza, 1976).

2.3 Soil Engineers: Ants, Termites, and Bioturbation

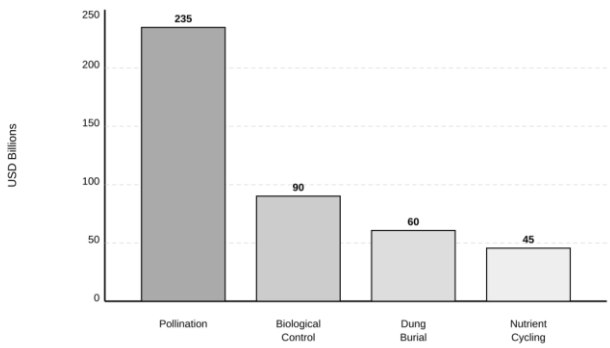
Beyond decomposition, insects physically restructure soil. Ants and termites are the primary insect groups responsible for bioturbation, the mixing of soil layers and the creation of macropores that improve water infiltration and root penetration. A mature leaf-cutter ant colony (Atta spp.) can excavate several tons of soil over its lifetime, moving mineral particles from depth to the surface and depositing organic waste in underground chambers that become nutrient hotspots (Farji-Brener and Werenkraut, 2017).

Termite mounds are similarly engineered structures. In African savannas, termite mounds concentrate nutrients to such a degree that the vegetation growing on and around them is visibly different from surrounding grassland, both in species composition and in productivity (Bonachela *et al*., 2015). These mounds function as nutrient islands, redistributing resources across landscapes in patterns that would not exist without the termites. The spatial heterogeneity they create has been shown to increase overall ecosystem productivity and support higher levels of animal diversity.

3. Ecosystem Services Provided by Insects

The Millennium Ecosystem Assessment (2005) categorized ecosystem services into four types: provisioning, regulating, supporting, and cultural. Insects contribute substantially to at least three of these categories. Pollination is a regulating service; decomposition and nutrient cycling are supporting services; and insects provide provisioning services as food for other organisms. The total economic value of insect ecosystem services has been estimated at hundreds of billions of dollars annually at the global scale (Noriega *et al*., 2018), though all such figures carry wide uncertainty ranges and should be treated as indicative rather than precise.

Figure 3. Estimated Annual Economic Value of Insect Ecosystem Services (Global)
(Based on Losey and Vaughan, 2006; values in USD billions, adjusted)



3.1 Pollination

Pollination is the most thoroughly studied and economically valued insect ecosystem service. Approximately 75% of the world's leading food crops depend to some extent on animal pollination, and insects, especially bees, carry out the majority of this work (Klein *et al*., 2007). The global economic value of insect pollination has been estimated at between $235 billion and $577 billion per year, depending on the methodology and assumptions used (IPBES, 2016; Potts *et al*., 2016). What makes the pollination story complex is that it is not just about honeybees. Wild pollinators, including bumblebees, solitary bees, hoverflies, and various moths and butterflies, frequently outperform managed honeybee colonies in terms of per-visit pollination efficiency for certain crops (Garibaldi *et al*., 2013). Strawberries, blueberries, cherries, and almonds all show improved fruit set when wild pollinators supplement honeybee visits. This matters because wild pollinator populations are declining in many regions, and honeybee management alone cannot fill the gap.

3.2 Biological Pest Control

Predatory and parasitoid insects suppress populations of herbivorous pests in both natural and agricultural ecosystems. Ladybird beetles (Coccinellidae) consume aphids; parasitoid wasps (Ichneumonidae, Braconidae) lay eggs in caterpillars; ground beetles (Carabidae) eat weed seeds and small invertebrates. The combined effect of these natural enemies is enormous. Losey and Vaughan (2006) estimated the value of biological pest control by native insects in the United States at approximately $4.5 billion per year in reduced crop losses, while a later global analysis put the figure closer to $100 billion when indirect benefits such as reduced pesticide use are included (Costanza *et al*., 2014).

There is a paradox in how agriculture relates to insect pest control. Intensive farming practices, particularly broad-spectrum insecticide application, tend to eliminate beneficial predators along with the target pests, which can lead to secondary pest outbreaks that are worse than the original problem. Integrated pest management (IPM) programs recognize this tension and attempt to use natural enemies more deliberately, but adoption remains uneven across regions and crop systems (Gurr *et al*., 2016).

3.3 Waste Decomposition and Sanitation

Insects perform sanitation services that are easy to take for granted until they are absent. Carrion-feeding beetles (Silphidae) and fly larvae (Calliphoridae, Sarcophagidae) rapidly break down animal carcasses, preventing the accumulation of decaying matter and reducing the risk of disease transmission. Similarly, dung-feeding insects remove animal waste from pasture surfaces, which limits habitat for livestock parasites such as horn flies and gastrointestinal nematodes (Fincher, 1981).

In forensic science, the predictable succession of insect species colonizing a corpse is used to estimate time of death, an applied reminder that insect decomposition follows orderly and reliable patterns. But the ecological importance is broader: without insect decomposers, dead organic matter accumulates, nutrients are locked in forms unavailable to plants, and disease vectors proliferate. Tropical ecosystems, where decomposition rates are highest, are most dependent on insect-mediated waste processing (Yang and Gratton, 2014).

4. Insects in Food Webs and Trophic Interactions

Insects occupy nearly every trophic level, and their position in food webs connects primary producers to higher-order consumers in ways that have far-reaching consequences for nutrient flow. As herbivores, insects channel plant-fixed carbon and nitrogen into animal biomass. As prey, they feed birds, bats, fish, amphibians, reptiles, and small mammals. As predators and parasitoids, they regulate the populations of other invertebrates. And as decomposers, they return nutrients to the soil, closing the loop.

Figure 4 Functional Groups of Insects in Ecosystem Services

Functional Group	Representative Taxa	Primary Service	Nutrient Process
Pollinators	Bees, butterflies, moths	Crop pollination	Indirect: fruit/seed set enables plant cycling
Detritivores	Termites, beetle larvae	Litter decomposition	Direct: fragment organic matter, release N and P
Coprophages	Dung beetles, flies	Dung removal/burial	Direct: bury dung, redistribute N in soil
Predators/Parasitoids	Ladybugs, wasps, beetles	Biological pest control	Indirect: regulate herbivore populations
Soil Engineers	Ants, termites, cicada	Soil structure/aeration	Direct: create pores, mix organic/mineral soil
Herbivores	Grasshoppers, aphids	Plant community regulation	Indirect: accelerate plant litter inputs

Figure 4 summarizes the primary functional groups of insects and their associated ecosystem services and nutrient processes. The diversity of roles is striking: the same class of organisms includes both the pollinators that enable crop reproduction and the decomposers that recycle the nutrients those crops will eventually need. This functional breadth is one of the reasons why insect declines are so concerning from an ecological standpoint. Losing insects does not just remove one node from the food web; it weakens connections across multiple trophic levels simultaneously.

Aquatic insects deserve separate mention. Mayfly, stonefly, and caddisfly larvae (Ephemeroptera, Plecoptera, Trichoptera) are dominant processors of leaf litter in freshwater streams, and their abundance is used as a standard indicator of water quality. When these insects emerge as adults, they transfer aquatic nutrients to terrestrial systems, subsidizing riparian food webs. Baxter *et al*. (2005) showed that emerging aquatic insects can provide more than half the annual energy budget for riparian spiders and some insectivorous bird species, illustrating how insect nutrient transfers cross ecosystem boundaries.

5. Threats to Insect Populations and Functional Consequences

The evidence for widespread insect decline has accumulated rapidly since the Krefeld study was published in 2017. While the magnitude and geographic scope of the decline remain subjects of debate, the general trend is difficult to contest. A global meta-analysis by van Klink *et al*. (2020) found that terrestrial insect abundance has declined by approximately 9% per decade, while freshwater insect populations have increased by about 11% per decade, possibly due to improved water quality regulations in some regions. The net picture is complex, but the terrestrial losses are real and consequential.

Figure 5 Reported Declines in Insect Biomass by Region

(Selected long-term monitoring studies, percentage decline over study period)

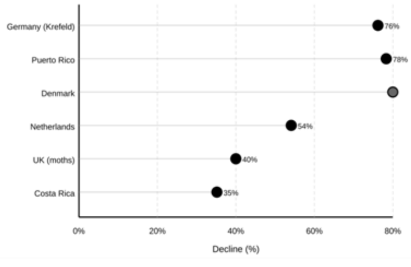


Figure 5 presents reported biomass declines from selected long-term monitoring studies. The highest losses have been documented in temperate Europe and the Caribbean, where habitat loss, pesticide use, light pollution, and climate change operate in combination. Sanchez-Bayo and Wyckhuys (2019) identified habitat change as the single largest driver of insect declines, followed by pollution (especially neonicotinoid insecticides), biological factors (pathogens and introduced species), and climate change. Their review, which covered 73 historical reports from around the world, concluded that 40% of insect species could face extinction within the coming decades if current trajectories persist.

From a nutrient cycling perspective, the loss of decomposer insects is particularly worrying. Experimental exclusion studies have shown that removing insects from litter decomposition systems reduces mass loss rates by 30 to 65 percent (Wall *et al*., 2008). In grassland experiments where dung beetles were excluded, dung pats persisted on the surface for months rather than weeks, nitrogen leaching increased, and pasture productivity declined measurably (Bang *et al*., 2005). These are not hypothetical scenarios; they are documented outcomes of insect absence.

The cascading effects extend beyond nutrient cycling. Insectivorous birds in European farmland have declined by more than 50% since 1980, and several studies have linked these declines directly to reduced insect food availability (Bowler *et al*., 2019). Bats, which consume vast quantities of insects nightly, face similar pressures. The loss of insect prey ripples through food webs in ways that compound over time and across trophic levels.

Discussion

The evidence reviewed here points to a conclusion that is straightforward but worth stating plainly: insects are among the most functionally important organisms in terrestrial ecosystems, and their contributions to nutrient cycling, pollination, pest control, and food web support are not easily replaced. The economic estimates, while imprecise, suggest that the services insects provide for free would cost hundreds of billions of dollars to replicate through technological or management alternatives.

One limitation of the existing literature is its geographic unevenness. Most long-term insect monitoring datasets come from Western Europe and North America, and the decomposition and nutrient cycling studies reviewed here are skewed toward tropical forests and temperate grasslands. We know comparatively little about insect-mediated nutrient flows in boreal systems, arid lands, and much of Asia and Africa. This gap matters because conservation interventions need local data to be effective, and global averages can obscure regional variation that is both ecologically and policy relevant. Another challenge is the difficulty of attributing specific nutrient fluxes to specific insect taxa. Most decomposition studies measure the aggregate effect of excluding all invertebrates, which includes mites, springtails, and earthworms alongside insects. Disentangling the insect-specific contribution requires controlled mesocosm experiments that are labor intensive and difficult to scale. Future research should prioritize taxon-specific functional assessments, particularly for the less-studied orders such as Psocoptera and Collembola, whose contributions to nutrient cycling may be underappreciated.

The policy implications are reasonably clear. Protecting insect biodiversity is not only a conservation objective in its own right; it is an investment in the continued functioning of agricultural and natural ecosystems. Reducing pesticide use, maintaining habitat heterogeneity at landscape scales, limiting light pollution, and addressing climate change are all interventions that have strong empirical support. The challenge, as with most environmental problems, is less about knowing what to do than about generating the political and economic will to do it.

Conclusion

Insects mediate nutrient cycling through decomposition, dung burial, and soil engineering, and they provide ecosystem services whose combined economic value runs into hundreds of billions of dollars per year. The documented declines in insect biomass across multiple continents threaten to disrupt these processes in ways that will be difficult and expensive to mitigate. Conservation of insect biodiversity is therefore not a peripheral concern but a practical necessity for maintaining the productivity and stability of the ecosystems on which human agriculture and well-being depend.

The research gaps identified in this review, including limited monitoring data from tropical and arid regions, insufficient taxon-specific functional studies, and uncertainty in economic valuation methods, should be addressed as priorities. In the meantime, the precautionary case for protecting insect habitat and reducing the chemical and physical pressures on insect populations is strong enough to act on without waiting for perfect data.

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