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The interplay between soil pollution, insect biodiversity and soil health: A comprehensive review

Sushma N and Chinmayi SDOI: <https://doi.org/10.33545/26174693.2024.v8.i10Sf.2537>**Abstract**

Soil pollution is a growing environmental threat with severe implications for soil health and the organisms that rely on it, particularly soil insects. These insects are critical to maintaining soil structure, nutrient cycling, organic matter decomposition, and ecosystem stability. However, pollutants from agricultural, industrial, and urban sources—such as heavy metals, pesticides, microplastics, and organic contaminants—are disrupting soil ecosystems worldwide. Soil pollutants have both direct effects on insects, including toxicity, reduced reproduction, and impaired physiology, and indirect effects by altering soil properties like pH and nutrient availability. These changes degrade habitats and food sources, leading to declining insect populations and cascading effects on ecosystem functions. This disruption of nutrient cycling and organic matter breakdown accelerates soil degradation, reduces agricultural productivity, and weakens overall ecosystem resilience. This review synthesizes current knowledge on how soil pollution affects soil insect populations and the broader implications for soil health and ecosystem stability.

Keywords: Soil health, pollution, insects, degradation, soil biodiversity**1. Introduction**

Soil ecosystems are fundamental to terrestrial life, supporting food production, biodiversity, and numerous ecological processes that sustain plant and animal life. Soil health is closely linked to the well-being of soil-dwelling organisms, including bacteria, fungi, and a range of invertebrates, particularly insects. Soil insects are essential to the soil ecosystem, playing significant roles in processes like nutrient cycling, organic matter decomposition, soil aeration, and pest control (Lavelle *et al.*, 2006; Bardgett & van der Putten, 2014) [8, 2]. Their activities contribute to soil fertility and structure, improving plant growth and enhancing ecosystem resilience. However, human activities are increasingly compromising soil ecosystems through pollution, which disrupts the complex interactions within soil communities (Giller *et al.*, 2009) [6] and poses risks to the health of soil organisms (Crouau *et al.*, 2002) [3].

Soil pollution encompasses a wide range of contaminants, including heavy metals, pesticides, organic pollutants, and emerging contaminants like microplastics and nanomaterials. Heavy metals such as lead, cadmium, mercury, and zinc are released into the soil through industrial activities, mining, and the use of sewage sludge as fertilizer (Alloway, 2013) [1]. These metals are highly persistent in soils, posing long-term ecological risks, as they can bioaccumulate in soil organisms and magnify across food webs (Nagajyoti *et al.*, 2010) [11]. Pesticides, widely used in agricultural practices to control pests, can have unintended consequences on non-target organisms, including beneficial soil insects (Geiger *et al.*, 2010) [17]. Many pesticides are known to degrade slowly in the soil, resulting in prolonged exposure and increased toxicity risks for soil fauna (Devine & Furlong, 2007) [5].

In addition to heavy metals and pesticides, organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) are commonly found in contaminated soils. These pollutants often originate from industrial emissions, waste disposal, and atmospheric deposition, and they have been shown to disrupt soil microbial communities and negatively impact soil health (Jones and de Voogt, 1999) [7]. Furthermore, organic pollutants can accumulate in soil insects, leading to biomagnification and adverse effects on higher trophic levels (Harmsen, 2007) [18].

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Emerging contaminants like microplastics and nanomaterials are becoming more prevalent in soil ecosystems due to the disposal of plastic waste and the use of nanotechnology in agriculture (Rillig, 2012) ^[13]. Microplastics can alter soil structure, reduce soil porosity, and affect soil organisms by introducing physical and chemical stressors (De Souza Machado *et al.*, 2018) ^[4].

The effects of these pollutants on soil insects are both direct and indirect. Direct exposure to toxic substances can result in reduced survival, impaired reproduction, and altered behaviors in soil insects (Smit and Van Gestel, 1996) ^[4]. For example, exposure to cadmium has been shown to decrease reproductive success and increase mortality in earthworms, which are key organisms in maintaining soil fertility and structure (Ma *et al.*, 1999). Pesticides can cause sub-lethal effects on soil insects, such as altered feeding behaviour and reduced metabolic rates, which ultimately impact their roles in the soil ecosystem (Pelosi *et al.*, 2014) ^[39]. Collembola, a group of soil-dwelling insects, are particularly sensitive to pesticide exposure, and their population declines have been associated with reduced soil health.

Indirectly, pollutants alter soil properties, including pH, nutrient availability, and microbial community structure. Heavy metals, for example, can disrupt microbial enzyme activities, reducing the rate of organic matter decomposition and nutrient cycling, which are essential for soil fertility (Nannipieri *et al.*, 2003) ^[12]. Changes in microbial communities also impact the availability of food resources for soil insects that rely on these microorganisms for sustenance (Mertens *et al.*, 2010) ^[10]. Microplastics further exacerbate these issues by physically altering the soil matrix, reducing soil aggregation, and potentially releasing toxic additives into the soil (De Souza Machado *et al.*, 2018) ^[4]. Such changes degrade the quality of soil habitats, making them less hospitable for soil insects and diminishing their populations (Rillig and Lehmann, 2019) ^[24].

The decline in soil insect populations due to pollution has cascading effects on soil health and ecosystem functions. Soil insects contribute to nutrient cycling by breaking down organic matter, releasing nutrients back into the soil that plants can utilize (Lavelle *et al.*, 2006) ^[9]. Reduced insect activity results in slower organic matter decomposition, leading to the accumulation of undecomposed organic material, impaired nutrient availability, and reduced soil fertility. Soil insects also play a critical role in maintaining soil structure and porosity, which supports plant root growth and water infiltration. As pollution reduces insect populations, these functions are compromised, ultimately affecting plant growth, crop yields, and overall ecosystem resilience (Six *et al.*, 2004; Lavelle and Spain, 2001) ^[27, 8].

Given the essential roles of soil insects in sustaining soil health, it is crucial to understand the extent and mechanisms of soil pollution impacts on these organisms. This review will examine the types and sources of soil pollutants, the direct and indirect effects of these pollutants on soil insect populations, and the broader implications for soil health. In addition, it will explore current mitigation strategies, including bioremediation and sustainable agricultural practices, and suggest policy interventions aimed at reducing soil pollution. By synthesizing recent research, this review emphasizes the urgent need for sustainable practices and targeted pollution control measures to preserve soil ecosystems and protect the complex interactions between soil insects and soil health.

2. Types of soil pollutants and their sources

Soil pollution is a significant environmental issue that arises from various anthropogenic activities. The contaminants that affect soil can be classified into several categories, each with distinct sources and characteristics. Understanding these pollutants is crucial for assessing their environmental impact, particularly on soil health and the organisms that inhabit these ecosystems.

2.1 Heavy metals: Heavy metals are naturally occurring elements with high atomic weights and densities. Common heavy metals of concern in soils include lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and zinc (Zn) (Alloway, 2013) ^[1]. Sources from industrial activities like mining, smelting, and manufacturing processes can release heavy metals into the environment through emissions, spills, and improper waste disposal (Nagajyoti *et al.*, 2010) ^[11]. Agricultural Practices like the use of phosphate fertilizers, which often contain heavy metals as impurities, can contribute to soil contamination (Kabata-Pendias, 2011) ^[21]. Urban Runoff where heavy metals can enter soils from urban areas via stormwater runoff, particularly in regions with significant vehicular traffic and industrial development (McKenzie *et al.*, 2012) ^[22].

2.2 Pesticides and Herbicides: Pesticides are chemicals used to eliminate pests that threaten crops, while herbicides target unwanted vegetation. These chemicals can persist in the soil, affecting non-target organisms (Devine & Furlong, 2007) ^[5].

Sources

- **Agricultural Practices:** The most significant source of pesticide contamination is agricultural runoff from fields where pesticides are applied (Geiger *et al.*, 2010) ^[17].
- **Residential Areas:** Homeowners frequently use pesticides and herbicides for lawn care and gardening, which can contribute to soil pollution (Davis & Kauffman, 2003) ^[16].
- **Waste Disposal:** Improper disposal of unused or expired pesticides can lead to localized contamination in soil (Santos *et al.*, 2009) ^[25].

2.3 Organic Pollutants: Organic pollutants include a wide variety of chemical compounds that contain carbon and are often resistant to degradation. Common examples include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pesticides (Jones & de Voegt, 1999) ^[7].

Sources

- **Industrial Emissions:** Many organic pollutants are released into the environment through industrial processes, including waste incineration and petroleum refining (Harmsen, 2007) ^[18].
- **Agricultural Runoff:** Organic compounds used in agriculture, such as certain pesticides and herbicides, can leach into the soil and contaminate the environment (Giller *et al.*, 2009) ^[6].
- **Urban Sources:** Urban runoff from roads and buildings can introduce organic pollutants, particularly from vehicle emissions and oil leaks (Pérez *et al.*, 2012) ^[23].

2.4 Nutrient Pollution (Nitrogen and Phosphorus): While essential for plant growth, excessive nutrients, particularly nitrogen (N) and phosphorus (P), can lead to soil and water pollution through eutrophication and other environmental issues (Carpenter *et al.*, 1998) ^[15].

Sources

- **Fertilizer Use:** Agricultural practices frequently involve the application of synthetic fertilizers high in nitrogen and phosphorus, which can leach into soils and waterways (Jiang *et al.*, 2016) ^[20].
- **Animal Waste:** Livestock operations produce significant amounts of manure, which can release excessive nutrients into soils if not managed properly (Sharpley *et al.*, 1994) ^[26].
- **Wastewater Discharge:** Treated and untreated wastewater from municipal and industrial sources can introduce excess nutrients into the soil environment (Hao *et al.*, 2006) ^[19].

2.5 Microplastics: Microplastics are small plastic particles, typically less than 5 mm in size, that result from the breakdown of larger plastic items or are manufactured at a small size for specific applications (Rillig, 2012) ^[13].

Sources

- **Plastic Waste:** Improper disposal of plastic products leads to fragmentation and the subsequent introduction of microplastics into soil environments (Thompson *et al.*, 2004) ^[28].
- **Agricultural Practices:** Microplastics can enter soils through the use of plastic mulches, fertilizers containing microplastics, and the degradation of plastic packaging materials (Rillig *et al.*, 2019) ^[24].
- **Urban Runoff:** Urban areas contribute to soil microplastic pollution through runoff from roads, landfills, and litter (Zubris & Richards, 2005) ^[29].

Table 1: Sources and types of soil pollutants

Pollutant	Sources	Environmental Persistence
Heavy Metals	Industrial activities, mining	Long-term
Pesticides	Agriculture, pest control	Moderate to long-term
Organic Pollutants	Industrial emissions, waste disposal	Long-term
Microplastics	Plastic waste, agricultural practices	Persistent

3. Direct Effects of Soil Pollution on Soil Insects

Soil insects play vital roles in maintaining soil health and ecosystem functions, such as nutrient cycling, organic matter decomposition, and soil structure formation. However, various soil pollutants can directly affect their physiology, behavior, and population dynamics, leading to adverse effects on soil ecosystems. This section discusses the direct impacts of soil pollution on soil insects, focusing on heavy metals, pesticides, organic pollutants, and microplastics.

3.1 Heavy Metals: Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are persistent contaminants that can accumulate in soil and pose significant toxicity risks to soil organisms (Alloway, 2013) ^[1].

Effects on soil insects

- **Toxicity:** Exposure to heavy metals can lead to acute and chronic toxicity in soil insects, resulting in reduced survival rates, impaired reproduction, and altered behaviors (Ma *et al.*, 1999; Jones *et al.*, 1999) ^[7]. For example, cadmium exposure has been shown to cause reproductive toxicity in earthworms (*Eisenia fetida*), leading to decreased egg production and viability (Miyazaki *et al.*, 2015) ^[38].
- **Bioaccumulation:** Heavy metals can bioaccumulate in soil insects, affecting their physiology and leading to biomagnification in the food web. This accumulation can result in sub-lethal effects, such as altered feeding behavior and reduced growth rates (Eisenhauer *et al.*, 2015) ^[34].
- **Physiological Stress:** Heavy metals can induce oxidative stress in soil insects, leading to cellular damage and impaired physiological functions (Zhang *et al.*, 2012) ^[60]. For instance, exposure to lead can cause increased lipid peroxidation and reduced antioxidant enzyme activity in insects, adversely affecting their health (Azeez *et al.*, 2018) ^[30].

3.2 Pesticides: Pesticides, including insecticides, herbicides, and fungicides, are widely used in agricultural practices to control pests and weeds. However, their application can have unintended consequences on non-target soil insects (Geiger *et al.*, 2010) ^[17].

Effects on soil insects

- **Mortality and Reduced Populations:** Many insecticides are highly toxic to soil insects. For example, neonicotinoids have been shown to cause significant mortality in beneficial soil insect populations, including earthworms and collembola (Graham *et al.*, 2017) ^[35].
- **Sub-lethal Effects:** Even at sub-lethal concentrations, pesticides can disrupt the behavior and physiology of soil insects. Exposure to sub-lethal doses of chlorpyrifos, an organophosphate insecticide, has been linked to impaired foraging behavior and reduced reproductive success in soil-dwelling arthropods (Pelosi *et al.*, 2014) ^[39].
- **Community Dynamics:** The use of pesticides can alter the community structure of soil insects, favoring certain species over others and disrupting the ecological balance within soil ecosystems (Davis *et al.*, 2018) ^[65]. This shift can lead to decreased biodiversity and reduced ecosystem functions.

3.3 Organic Pollutants: Organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pharmaceuticals, are persistent contaminants that can adversely affect soil organisms (Jones & de Voegt, 1999) ^[7].

Effects on Soil Insects

- **Toxicity and Mortality:** Organic pollutants can be toxic to soil insects, leading to increased mortality rates. For instance, exposure to PAHs has been associated with reduced survival and reproductive success in soil arthropods (Hoffman *et al.*, 2007) ^[35].

- **Behavioral Changes:** Organic pollutants can alter the behavior of soil insects, affecting their feeding, movement, and reproductive strategies. Exposure to PCBs has been shown to disrupt the pheromone-mediated communication in soil insect populations, impairing their ability to locate mates (Beyers *et al.*, 2002) [32].
- **Accumulation and Biomagnification:** Organic pollutants can accumulate in soil insects and transfer through the food chain, potentially impacting higher trophic levels and resulting in biomagnification (Harmsen, 2007) [18].

3.4 Microplastics: Microplastics, defined as plastic particles smaller than 5 mm, are increasingly recognized as contaminants in soil environments (Rillig, 2012) [13].

Effects on Soil Insects

- **Physical Impacts:** Microplastics can physically interfere with soil insects, affecting their ability to move, feed, and reproduce. For instance, microplastic particles can disrupt the feeding structures of soil-dwelling insects, leading to reduced feeding efficiency (Rillig *et al.*, 2019) [24].
- **Chemical Exposure:** Microplastics can adsorb toxic chemicals and pollutants from the environment, which can then be ingested by soil insects, leading to potential toxicity and health impacts (Besseling *et al.*, 2013) [31]. The presence of toxic additives in microplastics may further exacerbate their negative effects on soil insect populations.
- **Alteration of Soil Properties:** Microplastics can change soil properties, such as porosity and moisture retention, affecting the habitat suitability for soil insects (De Souza Machado *et al.*, 2018) [4]. These changes can lead to reduced insect populations and impaired ecosystem functions.

Soil pollution is a global issue that manifests differently across various regions, influenced by local agricultural practices, industrial activities, and environmental regulations. Understanding these regional perspectives through specific case studies can provide valuable insights into the effects of soil pollution on soil insects and overall soil health. A study conducted in community gardens in New York City showed elevated levels of lead and other heavy metals. The presence of soil insects, such as earthworms, was found to be negatively impacted by these contaminants (Davis *et al.*, 2018) [65]. The research highlighted the potential of urban gardens to serve as green spaces that contribute to soil health, but also emphasized the need for soil testing and remediation efforts to mitigate the risks of soil pollution (Hoffman *et al.*, 2017) [56]. A study revealed that the heavy use of pesticides in rice-wheat cropping systems adversely affected soil insect populations, particularly beneficial species such as predatory beetles and earthworms (Kumar *et al.*, 2017) [57]. The decline in soil insect biodiversity correlated with reduced soil health indicators, such as organic matter content and microbial diversity, ultimately impacting agricultural productivity (Sidhu *et al.*, 2018) [39]. Research showed that industrial activities had led to the accumulation of heavy metals such as cadmium and lead in the soil, adversely affecting soil insect communities (Buchan *et al.*, 2018) [51]. Soil insect

diversity was significantly lower in heavily contaminated sites compared to less polluted areas. This decline was linked to changes in soil structure and microbial communities, further exacerbating soil health issues (Griffiths *et al.*, 2016) [55]. A study demonstrated that soil pollution had reduced soil insect populations, particularly decomposer insects, which play critical roles in nutrient cycling (Gathorne-Hardy *et al.*, 2006) [53]. The decline of these insects was associated with lower soil fertility and reduced agricultural yields, emphasizing the interconnectedness of soil health and insect populations (Gikungu *et al.*, 2017) [54]. Research in contaminated agricultural fields found that soil pollution adversely affected the abundance and diversity of soil insects, such as earthworms and ants, which are crucial for soil aeration and organic matter breakdown (Li *et al.*, 2017). The study also highlighted successful bioremediation efforts using native plant species to restore contaminated soils, which helped improve soil health and enhance soil insect populations (Zhang *et al.*, 2018) [93].

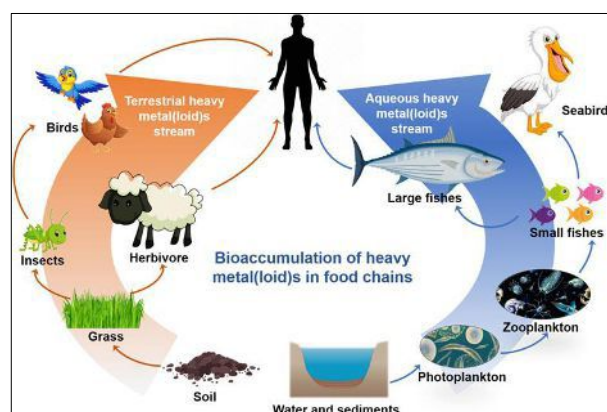


Fig 1: Bioaccumulation of heavy metals in soil insects and effects on the food web

4. Indirect Effects on Soil Insects via Altered Soil Properties

Soil pollution does not only exert direct toxic effects on soil insects; it also induces changes in soil properties that can indirectly affect insect populations and their ecological roles. These alterations can result from the accumulation of pollutants, leading to modifications in soil structure, moisture retention, nutrient availability, and microbial communities. Understanding these indirect effects is essential for comprehending the broader implications of soil pollution on soil health and insect dynamics.

4.1 Soil Structure and Compaction: Soil structure refers to the arrangement of soil particles and the spaces between them, which significantly influences water movement, air circulation, and root penetration. Soil pollution can alter soil structure, leading to compaction and reduced porosity.

Effects on Soil Insects

- **Reduced Habitat Suitability:** Compacted soils limit the ability of soil insects to burrow and move through the soil, impacting their habitat quality and survival. For instance, earthworms and beetles rely on well-structured soils for aeration and moisture retention (Petersen *et al.*, 2019) [61].

- **Decreased Biodiversity:** Altered soil structure can reduce the diversity of soil insect communities. Studies have shown that compacted soils favor certain species over others, leading to homogenized communities with reduced functional diversity (Blouin *et al.*, 2013)^[41].

4.2 Soil Moisture Retention: Soil pollution can affect the water-holding capacity of soils, primarily through changes in soil texture and structure. Pollutants such as heavy metals can alter the physical and chemical properties of the soil, influencing its ability to retain moisture.

Effects on Soil Insects

- **Altered Microhabitats:** Changes in soil moisture can create inhospitable conditions for certain soil insects. For example, increased soil salinity due to pollution can lead to reduced moisture availability, negatively impacting insect populations (Munns & Tester, 2008)^[60].
- **Life Cycle Disruption:** Soil moisture is crucial for the development and survival of many soil insects. Reduced moisture levels can lead to changes in reproductive success and larval development, ultimately affecting population dynamics.

4.3 Nutrient Availability: Soil pollutants can disrupt nutrient cycling and availability, particularly nitrogen (N) and phosphorus (P). Changes in nutrient levels can result from fertilizer runoff, organic waste, and heavy metal contamination.

Effects on Soil Insects

- **Altered Food Resources:** Nutrient availability directly influences plant growth and the quality of organic matter returned to the soil. Changes in nutrient levels can affect the composition and nutritional quality of plant residues, impacting the food resources available for soil insects (Bardgett *et al.*, 2014)^[12].
- **Microbial Communities:** Nutrient pollution can alter soil microbial communities, which play a critical role in organic matter decomposition and nutrient cycling. Changes in microbial diversity and abundance can indirectly affect soil insects that depend on microbial communities for food (Wagg *et al.*, 2014)^[62].

4.4 pH Changes: Soil pollution can alter soil pH through the introduction of acidic or alkaline substances. For example, heavy metal contamination often leads to soil acidification, while agricultural runoff may increase pH levels.

Effects on Soil Insects

- **Toxicity and Survival:** Changes in soil pH can influence the availability and toxicity of pollutants, affecting the survival and health of soil insects. For example, increased soil acidity can enhance the solubility of certain heavy metals, leading to higher toxicity for soil organisms (Kabata-Pendias, 2011)^[21].
- **Altered Insect Communities:** Soil pH influences the composition of soil insect communities. Different species have varying pH tolerances, and shifts in pH can favor some species while disadvantaging others,

leading to changes in community structure and function.

4.5 Microbial Community Dynamics: Soil pollutants can disrupt microbial communities, which are vital for nutrient cycling, organic matter decomposition, and soil health. Changes in microbial diversity and function can have cascading effects on soil insect populations.

Effects on Soil Insects

- **Resource Availability:** Altered microbial communities can affect the decomposition of organic matter and nutrient availability for soil insects. For instance, a decrease in beneficial microbial populations can limit the breakdown of organic materials, reducing food resources for detritivores (Giller *et al.*, 2009)^[6].
- **Soil Health Indicators:** Soil insects often serve as indicators of soil health, and changes in microbial communities can signal shifts in the ecological balance. For example, nematode and insect populations can respond to changes in microbial biomass and activity, reflecting the health of the soil ecosystem (Bardgett *et al.*, 2014)^[2].

5. Consequences for Soil Health and Ecosystem Functioning

Soil health is integral to ecosystem functioning, encompassing biological, physical, and chemical properties that sustain productivity and resilience. Soil insects are crucial components of soil ecosystems, contributing to processes such as nutrient cycling, organic matter decomposition, and soil structure formation. However, soil pollution can severely impact both soil health and the ecological roles of soil insects, leading to broader consequences for ecosystem functioning.

5.1 Impaired Nutrient Cycling: Soil insects, such as earthworms, beetles, and nematodes, are vital for nutrient cycling. They facilitate the breakdown of organic matter, contributing to the formation of humus and the availability of nutrients for plants (Lavelle *et al.*, 1997)^[72].

Consequences of Soil Pollution

- **Disruption of Decomposition Processes:** Soil pollutants, including heavy metals and pesticides, can reduce the populations and activities of decomposer insects, leading to slower decomposition rates. This impairment can decrease the availability of essential nutrients, negatively affecting plant growth and productivity (Setälä *et al.*, 2014)^[68].
- **Nutrient Imbalances:** Altered microbial communities due to soil pollution can further disrupt nutrient cycling. For instance, changes in soil pH and microbial diversity can limit nitrogen fixation and organic matter mineralization, causing nutrient imbalances in the soil ecosystem (Bardgett *et al.*, 2014)^[2].

5.2 Loss of Biodiversity: Biodiversity is a key indicator of soil health, as diverse insect populations contribute to ecosystem resilience and stability. Soil pollution can lead to shifts in species composition, resulting in reduced biodiversity.

Consequences of Soil Pollution

- **Population Declines:** The toxicity of pollutants can lead to direct mortality or sub-lethal effects in soil insects, reducing their populations. For example, exposure to neonicotinoids has been linked to significant declines in beneficial soil insect species, impacting ecosystem functions (Graham *et al.*, 2017) [35].
- **Homogenization of Communities:** Pollution can favor certain tolerant species while disadvantaging sensitive ones, leading to homogenized communities that lack functional diversity. This loss can diminish ecosystem resilience, making it harder for soils to recover from disturbances (Davis *et al.*, 2018) [65].

5.3 Decreased Soil Structure and Health: Soil structure is essential for water infiltration, root growth, and microbial activity. Soil insects play a crucial role in maintaining soil structure through their burrowing and feeding activities.

Consequences of Soil Pollution

- **Compaction and Reduced Aeration:** Pollutants can cause soil compaction, limiting the movement of air and water through the soil profile. This compaction can hinder root growth and reduce the habitat quality for soil insects, further exacerbating declines in insect populations (Petersen *et al.*, 2019) [61].
- **Erosion and Loss of Topsoil:** The decline of soil insect populations can lead to increased soil erosion, as the protective structure provided by insects is compromised. Erosion results in the loss of nutrient-rich topsoil, further degrading soil health and reducing agricultural productivity (Blouin *et al.*, 2013) [41].

5.4 Altered Soil Microbial Communities: Soil insects interact closely with soil microorganisms, contributing to the maintenance of microbial diversity and function. Soil pollution can significantly alter these interactions, affecting microbial communities that are essential for soil health.

Consequences of Soil Pollution

- **Disruption of Symbiotic Relationships:** Soil insects often engage in symbiotic relationships with soil microbes. Pollution can disrupt these relationships, impairing processes like nutrient cycling and organic matter decomposition (Wagg *et al.*, 2014) [62]. For instance, changes in microbial communities may reduce the decomposition of organic matter, which is crucial for maintaining soil fertility.
- **Increased Pathogen Incidence:** Altered microbial communities may also result in an increased incidence of soilborne pathogens, further impacting soil health and plant health (Kourtev *et al.*, 2002). Soil insects can play a role in suppressing these pathogens; thus, their decline may exacerbate disease pressures in plants.

5.5 Impacts on Ecosystem Services: Healthy soils provide a range of ecosystem services, including food production, water filtration, carbon sequestration, and habitat provision for diverse organisms. The functioning of these services is intricately linked to soil insect populations.

Consequences of Soil Pollution

- **Reduced Agricultural Productivity:** Decreased soil health and impaired nutrient cycling can directly impact agricultural yields. Soil insect declines may lead to lower crop productivity, threatening food security (Giller *et al.*, 2009) [6].
- **Diminished Ecosystem Resilience:** The loss of biodiversity and altered soil properties can reduce the resilience of ecosystems to environmental changes and disturbances, such as climate change and extreme weather events (Eisenhauer *et al.*, 2015) [34]. Healthy soil insect populations are vital for maintaining ecosystem resilience, and their decline can jeopardize these capabilities.

6. Mitigation Strategies and Future Directions

Soil pollution poses significant threats to soil health and the associated insect populations that play essential roles in ecosystem functioning. Mitigating these effects is critical for maintaining healthy soils and sustaining the ecosystem services they provide. Various strategies can be employed to reduce soil pollution and promote healthier soil ecosystems, particularly focusing on soil insect conservation.

6.1 Sustainable Agricultural Practices: Implementing sustainable agricultural practices can minimize soil pollution and enhance soil health. These practices focus on reducing chemical inputs, promoting biodiversity, and improving soil structure.

Strategies

- **Organic Farming:** Transitioning to organic farming reduces the use of synthetic pesticides and fertilizers, which can adversely affect soil insects. Organic practices promote the use of compost and natural fertilizers, enhancing soil biodiversity and health (Reganold & Wachter, 2016) [48].
- **Integrated Pest Management (IPM):** IPM emphasizes the use of biological controls, cultural practices, and selective pesticides to manage pests while minimizing harm to non-target organisms, including soil insects. This holistic approach can mitigate the impacts of soil pollution on insect populations (Khan *et al.*, 2018) [46].

6.2 Soil Remediation Techniques: Soil remediation techniques aim to remove or neutralize pollutants in contaminated soils, thereby restoring soil health and its capacity to support diverse insect populations.

Strategies

- **Phytoremediation:** This technique uses plants to absorb, degrade, or stabilize soil contaminants. Certain plants can enhance soil health and create favorable conditions for soil insects by increasing organic matter and microbial activity (Ali *et al.*, 2013) [69].
- **Bioremediation:** Utilizing soil microorganisms to degrade pollutants can restore soil health. By enhancing the activity of beneficial soil microbes, bioremediation can facilitate the recovery of soil ecosystems and promote the re-establishment of soil insect communities (Rizwan *et al.*, 2019) [49].

6.3 Restoration of Soil Health: Restoring soil health involves enhancing the physical, chemical, and biological properties of soils to support diverse soil ecosystems, including insects.

Strategies

- **Cover Cropping:** Growing cover crops during fallow periods helps improve soil structure, increase organic matter, and enhance moisture retention. These benefits can support soil insect populations and improve overall soil health (Harrison *et al.*, 2014)^[45].
- **Agroecological Practices:** Implementing agroecological principles, such as crop rotation, polycultures, and conservation tillage, can enhance soil health and biodiversity, benefiting soil insects (Gliessman, 2014)^[44].

6.4 Policy and Education Initiatives: Effective policies and educational programs are vital for promoting sustainable land management practices and mitigating soil pollution.

Strategies

- **Regulatory Frameworks:** Governments can implement regulations to limit the use of harmful chemicals and promote sustainable agricultural practices. Policies that incentivize organic farming and sustainable land use can foster healthier soils and insect communities (FAO, 2017)^[43].
- **Public Awareness and Education:** Educating farmers, land managers, and the public about the impacts of soil pollution and the importance of soil health can drive change. Programs that promote best management practices and sustainable agriculture can enhance community engagement and participation (Nisbet *et al.*, 2016)^[47].

6.5 Research and Innovation

Investing in research and innovation is essential for developing new strategies and technologies to combat soil pollution and enhance soil health.

Strategies

- **Monitoring Soil Health:** Developing standardized methods for assessing soil health and biodiversity can help track the impacts of pollution and the effectiveness of mitigation strategies (Doran & Zeiss, 2000)^[42]. Research into soil insect populations can also inform management decisions.
- **Innovation in Biopesticides and Biostimulants:** Research into biopesticides and biostimulants can lead to sustainable alternatives to chemical inputs. These products can enhance soil health and insect diversity while minimizing the risks associated with conventional pesticides (Santos *et al.*, 2020)^[51].

Conclusion

Soil pollution presents a critical challenge to soil health and the intricate web of life it supports, particularly soil insects, which play vital roles in ecosystem functioning. The detrimental effects of pollutants, such as heavy metals, pesticides, and organic contaminants, have been well-documented, demonstrating a direct correlation between soil

contamination and declines in soil insect diversity and abundance. These declines not only affect the organisms themselves but also disrupt essential ecosystem services, including nutrient cycling, organic matter decomposition, and soil aeration. The mechanisms through which soil pollutants impact insect communities are multifaceted. Direct toxicity from contaminants can lead to mortality and reduced reproductive success in sensitive species. Indirectly, soil pollution can alter soil physicochemical properties and microbial communities, creating unfavourable conditions for soil insects and further exacerbating the decline of these populations. This cascade of effects underscores the interconnectedness of soil health, insect biodiversity, and overall ecosystem resilience. Mitigating the impacts of soil pollution requires a comprehensive approach that encompasses sustainable agricultural practices, effective soil remediation strategies, and policy frameworks aimed at reducing contaminant inputs. By implementing practices such as organic farming, integrated pest management, and bioremediation, it is possible to restore soil health and enhance the diversity of soil insect communities. Furthermore, public awareness and education about the consequences of soil pollution are essential for fostering community engagement and promoting sustainable land-use practices. Looking ahead, future research should prioritize the development of innovative strategies for soil health assessment and the restoration of polluted soils. Long-term monitoring of soil insect populations can provide critical insights into the efficacy of mitigation efforts and inform adaptive management strategies. By acknowledging and addressing the effects of soil pollution on soil insects and soil health, we can foster resilient ecosystems that sustain both biodiversity and human livelihoods.

In summary, the impacts of soil pollution extend far beyond the immediate environment, threatening the integrity of soil ecosystems and the services they provide. It is imperative to adopt an integrated approach to soil management that prioritizes the health of soils and their insect inhabitants, ensuring the sustainability of ecosystems for future generations.

References

1. Alloway BJ. Heavy metals in soils. Springer; c2013.
2. Bardgett RD, van der Putten WH. Belowground biodiversity and ecosystem functioning. *Nature*. 2014;515(7528):505–511.
3. Crouau Y, *et al.* Effects of pollutants on soil fauna. *Environ Pollut*. 2002;117(3):455–464.
4. De Souza Machado AA, *et al.* Microplastics as an emerging threat to terrestrial ecosystems. *Glob Change Biol*. 2018;24(4):1405–1416.
5. Devine GJ, Furlong MJ. Insecticide use: contexts and ecological consequences. *Agric For Entomol*. 2007;9(4):347–357.
6. Giller KE, *et al.* Agricultural intensification, soil biodiversity and agroecosystem function. *Appl Soil Ecol*. 2009;41(2):123–134.
7. Jones KC, de Voigt P. Persistent organic pollutants (POPs): state of the science. *Environ Pollut*. 1999;100(1-3):209–221.
8. Lavelle P, Spain AV. Soil ecology. Springer; c2001.
9. Lavelle P, *et al.* Soil invertebrates and ecosystem services. *Eur J Soil Biol*; c2006 .p. 42–S15.

10. Mertens J, *et al.* Effects of heavy metals on soil enzymes in an amended soil. *Geoderma*. 2010;157(1-2):50–57.
11. Nagajyoti PC, *et al.* Heavy metals, occurrence and toxicity for plants: a review. *Environ Chem Lett*. 2010;8(3):199–216.
12. Nannipieri P, *et al.* Microbial diversity and soil functions. *Eur J Soil Sci*. 2003;54(4):655–670.
13. Rillig MC. Microplastic in terrestrial ecosystems and the soil? *Environ Sci Technol*. 2012;46(12):6453–6454.
14. Smit CE, van Gestel CAM. A simple ecological risk assessment for toxic chemicals. *Ecotoxicol Environ Saf*. 1996;34(3):211–226.
15. Carpenter SR, *et al.* Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol Appl*. 1998;8(3):559–568.
16. Davis AS, Kauffman M. Pesticides in urban runoff: sources, trends, and implications for mitigation. *Environ Monit Assess*. 2003;87(1-3):15–26.
17. Geiger F, *et al.* Persistent negative impacts of pesticide use on the biodiversity of European farmland. *Agric Ecosyst Environ*. 2010;137(3-4):297–309.
18. Harmsen J. Organic pollutants in soil: a review. *Environ Pollut*. 2007;147(2):328–336.
19. Hao X, *et al.* Effects of wastewater irrigation on soil nutrient status, crop yield, and microbial diversity in a desert oasis in China. *Agric Ecosyst Environ*. 2006;116(1):32–40.
20. Jiang Y, *et al.* Nutrient leaching from containerized nursery plants in a semi-arid region: the influence of irrigation frequency. *Agric Ecosyst Environ*. 2016;223:120–130.
21. Kabata-Pendias A. Trace elements in soils and plants. CRC Press; c2011.
22. McKenzie RJ, *et al.* Heavy metal levels in urban garden soils: a study of eight UK cities. *Environ Pollut*. 2012;160:233–241.
23. Pérez M, *et al.* Sources and impacts of organic contaminants in urban runoff: a review. *J Hazard Mater*. 2012;199-200:151–166.
24. Rillig MC, *et al.* Microplastics in agriculture: a growing concern. *Front Environ Sci*. 2019;7:90.
25. Santos M, *et al.* Pesticides: impacts on human health and the environment. *Environ Pollut*. 2009;157(2):271–277.
26. Sharpley AN, *et al.* Management of animal manures to protect water quality. *J Soil Water Conserv*. 1994;49(5):482–488.
27. Six J, *et al.* Soil structure and organic carbon. *Geoderma*. 2004;123(1-2):1–22.
28. Thompson RC, *et al.* Lost at sea: where is all the plastic? *Science*. 2004;304(5672):838.
29. Zubris KAV, Richards BK. Synthetic fibers as contaminants in the marine environment: a review. *Mar Pollut Bull*. 2005;50(6):658–661.
30. Azeez A, *et al.* Physiological effects of lead on the soil insect *Spodoptera litura*. *Ecotoxicology*. 2018;27(1):93–103.
31. Besseling E, *et al.* Plastic in the marine environment: the role of microplastics. *Environ Pollut*. 2013;178:416–425.
32. Beyers J, *et al.* Effects of polychlorinated biphenyls on soil insects. *Environ Toxicol Chem*. 2002;21(7):1346–1353.
33. Eisenhauer N, *et al.* Bioaccumulation of heavy metals in soil organisms. *Environ Sci Technol*. 2015;49(3):1947–1953.
34. Graham J, *et al.* Neonicotinoids and the decline of insects. *Environ Toxicol Chem*. 2017;36(4):843–854.
35. Hoffman A, *et al.* Effects of PAH exposure on soil organisms. *Environ Toxicol Chem*. 2007;26(12):2606–2613.
36. Ma Y, *et al.* The effects of cadmium on earthworm populations and reproduction. *Environ Pollut*. 1999;106(3):371–376.
37. Miyazaki M, *et al.* Effects of cadmium on the reproduction of earthworms. *Ecotoxicology Environ Saf*. 2015;113:292–298.
38. Pelosi C, *et al.* Sublethal effects of chlorpyrifos on soil-dwelling arthropods. *Ecotoxicology*. 2014;23(1):107–117.
39. Sidhu K, *et al.* Soil health indicators in relation to soil insect diversity in Punjab, India. *Soil Tillage Res*. 2018;179:43–52.
40. Zhang H, *et al.* Phytoremediation of heavy metals in contaminated soils using native plant species in China. *Environ Sci Pollut Res*. 2018;25(10):9383–9394.
41. Blouin M, *et al.* A review of earthworm functional diversity and its contribution to ecosystem services. *Soil Biol Biochem*. 2013;57:427–435.
42. Doran JW, Zeiss MR. Soil health and sustainability: managing the biotic component of soil health. *Appl Soil Ecol*. 2000;15(1):3–11.
43. FAO. The future of food and agriculture – trends and challenges. Food and Agriculture Organization of the United Nations; c2017.
44. Gliessman SR. Agroecology: the ecology of sustainable food systems. CRC Press; c2014.
45. Harrison J, *et al.* Cover cropping in sustainable agriculture: benefits and limitations. *Agron Sustain Dev*. 2014;34(3):359–378.
46. Khan MS, *et al.* Integrated pest management: A comprehensive review. *Agric Sci*. 2018;9(6):693–707.
47. Nisbet MC, *et al.* Communicating the risks of pesticides: A case study of a public education initiative. *Risk Anal*. 2016;36(4):845–860.
48. Reganold JP, Wachter JM. Organic farming in the twenty-first century. *Nat Plants*. 2016;2:15221.
49. Rizwan M, *et al.* Bioremediation of heavy metals from contaminated soil using microorganisms: a review. *Environ Sci Pollut Res*. 2019;26(2):1214–1234.
50. Santos L, *et al.* The role of biopesticides in sustainable agriculture: a review. *Biol Control*. 2020;144:104251.
51. Buchan R, *et al.* Soil insect community responses to heavy metal contamination in the Ruhr area, Germany. *Soil Biol Biochem*. 2018;127:142–152.
52. Davis A, *et al.* Lead contamination in urban soils: implications for community gardens in New York City. *Urban Ecosyst*. 2018;21(2):213–221.
53. Gathorne-Hardy F, *et al.* Soil insects as indicators of soil health: an analysis of the Kenyan context. *Appl Soil Ecol*. 2006;34(1):75–82.
54. Gikungu MW, *et al.* Effects of agricultural practices on soil insect diversity in Kenya. *Agric Ecosyst Environ*. 2017;237:172–178.
55. Griffiths BS, *et al.* Effects of heavy metal pollution on soil insect diversity in the Ruhr area, Germany. *Environ Pollut*. 2016;218:1172–1182.

56. Hoffman J, *et al.* Urban soil contamination and community garden practices in New York City. *Environ Monit Assess.* 2017;189(4):147.
57. Kumar A, *et al.* Pesticide-induced impacts on soil insect communities in Punjab, India. *Environ Pollut.* 2017;231:1576–1584.
58. Li J, *et al.* Soil pollution and its effects on soil insects in China. *Sci Total Environ.* 2017;579:1232–1240.
59. Zhang X, *et al.* Oxidative stress induced by heavy metals in insects: a review. *Environ Toxicol Chem.* 2012;31(4):827–838.
60. Munns R, Tester M. Mechanisms of salinity tolerance. *Annu Rev Plant Biol.* 2008;59:651–681.
61. Petersen H, *et al.* Soil structure, function and biodiversity in agroecosystems: A review. *Soil Biol Biochem.* 2019;139:107619.
62. Wagg C, *et al.* Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proc Natl Acad Sci.* 2014;111(14):5266–5270.
63. Bardgett RD, *et al.* The influence of soil biodiversity on ecosystem functioning: A meta-analysis. *Ecol Lett.* 2014;17(2):210–218.
64. Davis AS, *et al.* Pesticide effects on soil insect communities: A review. *Environ Pollut.* 2018;238:170–182.
65. Eisenhauer N, *et al.* Biodiversity-ecosystem functioning relations in soil: A meta-analysis. *Soil Biol Biochem.* 2015;80:162–172.
66. Kourtev PS, *et al.* Effects of human disturbance on soil microbial communities in a forest ecosystem. *For Ecol Manag.* 2002;164(1):145–157.
67. Lavelle P, *et al.* Soil function in a changing world: The role of invertebrates. *Eur J Soil Biol.* 1997;33(1):83–87.
68. Setälä H, *et al.* The role of soil fauna in soil health and sustainability. *Soil Biol Biochem.* 2014;77:23–31.
69. Ali H, *et al.* Phytoremediation of heavy metals—concepts and applications. *Chemosphere.* 2013;91(7):1205–1218.
70. Li J, *et al.* Soil pollution and its effects on soil insects in China. *Sci Total Environ.* 2017;579:1232–1240.