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The Relationship between Soil Structure and Insect Biodiversity

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The Relationship between Soil Structure and Insect Biodiversity

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1. Introduction

Soil is an important habitat for insects, providing essential nutrients, shelter, and breeding grounds. It influences insects in a variety of ways, and insects in turn influence soil health (Bennett, 2010). Insect biodiversity refers to the variety and variability of insect species within an ecosystem, including genetic diversity, species diversity, and ecological diversity (Wagner et al., 2021). Soil structure refers to the arrangement of soil particles and pores, which determines water retention, aeration, and microbial activity (Bennett, 2010).

Historically, urbanization is one of the main land-use changes behind global insect collapse (Sánchez-Bayo & Wyckhuys, 2019). Urbanization has significantly altered soil structures, leading to compaction, nutrient depletion, and insect habitat degradation (Sánchez-Bayo & Wyckhuys, 2019). These changes have contributed to declines in insect populations by disrupting their essential soil functions. Most previous studies on insect biodiversity are correlational and do not pinpoint the potential factors leading to its decline, and are on a broad, global scope rather than being environmentally specific (McDonnell & Hahs, 2013). Therefore, while this paper does not seek to establish causality, it aims to specifically examine how soil structure relates to insect biodiversity, within urban settings.

During urbanization, soil aeration and soil organic content are two key factors that have been impacting soil biodiversity the most (Bennett, 2010). This paper will explore if healthy, well-aerated, and organic-rich soils typically support higher insect biodiversity, and whether urban environments tend to exhibit lower levels of insect biodiversity.

2. Impact of Soil Structure on Insect Biodiversity

Soil structure is determinant of insect biodiversity, as it directly influences their dispersal, habitat availability, moisture levels, and nutrient cycling (Buchholz & Egerer, 2020). There are various types of influences, with the major ones, related to soil aeration and organic content, being discussed below.

Soil Compaction on Insect Habitats

Human activities, particularly agricultural practices and urban development, contribute to soil compaction. This significantly reduces soil aeration and habitat availability for insects (Farji-Brener, 2008). Compacted soils usually have fewer soil air spaces, which are essential for insects' nesting, foraging, and protection. Thus, the decline of these microhabitats leads to decline in insect populations (Kessel, 2019). Compacted soil also limits water permeability, affecting oxygen and moisture availability, both of which impact insect life cycles (Moreira et al., 2025).

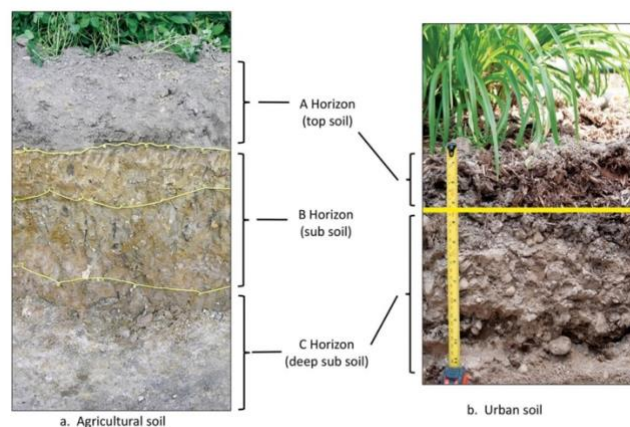


Figure 1 A comparison of natural and compacted soils. The agricultural soil (natural) on the left shows multiple distinct soil horizons, whereas the urban soil (compacted) shows only two layers, with the B Horizon missing. Each layer is also thinner than that of the natural soil. (Kessel, Urban Soils: Naturally unnatural, 2019)

Previous studies have shown that insect populations tend to decrease in areas where heavy machinery and construction compacted natural soil structures, because these changes alter the conditions necessary for insect burrowing and feeding (Wagner et al., 2021; Kessel, 2019). Ideally, soils consist of 50 per cent physical matter, such as minerals and organic matter, and 50 per cent pore space for air and water (Kessel, 2019). However, many compacted soils, especially in urban area, have only 20-30 per cent pore space, leaving little habitats and oxygen for soil insects, causing a decrease in their biodiversity (Kessel, 2019). The impact of urban soil on insects will be further discussed in later sections of this paper.

Organic Matter and Insect Biodiversity

Soils with high organic content support diverse insect populations by providing abundant food sources and an interconnected ecosystem, namely microbe communities (Blanche & Westoby, 1995). Many insects, particularly decomposers and detritivores, depend on nutrient availability for survival. Springtails, dung beetles, and larvae of some Hymenoptera, for example, feed on organic material in the soil (Buchholz & Egerer, 2020). Furthermore, organic matter also contributes to soil aggregation, creating microhabitats suitable for insect colonization (Blanche & Westoby, 1995).

Microbes contribute significantly to soil's overall fertility and stability, indirectly impacting insect biodiversity. Bacteria and fungi play key roles in decomposition processes by breaking down organic materials and releasing nutrients that support plant and insect life (Blanche & Westoby, 1995). For example, some termite species rely on symbiotic bacteria to digest cellulose, allowing them to process plant materials (Blanche & Westoby, 1995). Thus, a diverse microbial community enhances soil health, creating favorable conditions to support a high insect diversity.

Overall, healthy, well-aerated, and organic rich soil tend to support higher insect biodiversity. The next section is to examine if high insect biodiversity would in turn support soil health and form positive feedback.

3. Impact of Insects on Soil Systems

The relationship between soil and insects is mutual. There are positive feedback loops between soil and insects, especially through plants (Bennett, 2010). Studies show that soil health can significantly impact plant productivity, and the size and health of the plant root system directly affect insect abundance and diversity by providing habitats and food sources (Bennett, 2010). In turn, insects can also stabilize soil conditions. For example, beetles and ants contribute to soil aeration by creating tunnels that introduce oxygen flow into the soil (Bennett, 2010). Insects' nesting behaviors also modify soil properties. For example, termites construct intricate mounds that can alter soil texture and structure, creating more ecological niches to support more soil microbe communities (Bennett, 2010).

Furthermore, plant root systems significantly influence insect populations. Root exudates, which consist of organic compounds released by plants, support microbial growth and thus more food sources for soil-dwelling insects (Thompson, 2022). Root systems also contribute to soil stability by preventing erosion from wind and water, securing insects' burrowing and nesting (Thompson, 2022). The interdependent relationship between soil structure and insect biodiversity, forming positive feedback, supports and stabilizes the soil ecosystem.

4. Impact of Urbanization on Soil Insect Biodiversity

This section of the paper will zoom into soil-insect interactions in urban areas. Cities are complex and heterogeneous landscapes characterized by large proportions of impervious surfaces, high levels of habitat fragmentation, elevated temperatures, high pollution levels, and the occurrence of many non-native species (Grimm et al., 2008). According to this definition, four main urban factors, due to their ability to produce disproportionately large impacts on insects, are concluded from previous studies and being discussed here: impervious surfaces, habitat fragmentation, pollution, and urban heat island effect (Fenoglio et al., 2021; Grimm et al., 2008).

Impervious Surfaces

Urbanization often led to ground surfaces sealed by cement and concrete, which are impermeable materials, leading to an increase in impervious surfaces. This soil sealing, which reduces the water and air from entering soil, would hinder water infiltration, air passage, and thus insect biodiversity (Scalenghe & Marsan, 2009). Therefore, it reduces soil aeration and humidity, making urban soils less hospitable for many insects. It also posts a physical barrier to insect movement, limiting their burrowing activities (Scalenghe & Marsan, 2009).

Impervious surfaces also disrupt the hydrological cycle. It increases surface runoff and the soil erosion caused by it, further reducing the habitat available for insects (Ahrne et al., 2009). Its prevention of water infiltration makes the soil drier and less able to sustain insects that needs high moisture levels to hatch or survive, such as bumble bees (Ahrne et al., 2009). Furthermore, since compacted soils reduce fauna biodiversity, soil processes like nutrient cycling

are reduced, making the overall soil system unstable and less able to support a diverse insect community. In all, fewer species are able to establish in urban soil with impervious surfaces.

Habitat Fragmentation and Pollution

Urbanization's largest impact on habitats is the fragmentation of them into patches that vary in size and isolation, accompanied by habitat loss and changes in landscape structure (Liu et al., 2016). Small habitat patches tend to support less diverse insect communities, and the degree of isolation is negatively correlated with insect diversity (Fattorini et al., 2018). This is mainly due to that habitat fragmentation disrupts the continuity of soil systems and makes it difficult for insects to migrate, disperse, and recolonize between habitat patches (Fattorini et al., 2018). This also in turn negatively impacts soil structure, as important soil organisms like earthworms, ants, and beetles, whose activities promote soil aeration and organic matter decomposition, are reduced (Fattorini et al., 2018).

Urban environment also exerts significant edge effects on soils in fragmented habitats (Soga et al., 2013). A larger edge effect enables surrounding anthropogenic pollution to impact the soil ecosystem more (Srivastava et al., 2021). For example, electromagnetic pollution leaking from mobile cell components at sites of disposal has been reducing the reproductive potential in fruit fly *Drosophila melanogaster* and reduced successful hatching in honeybee *Apis mellifera* (Redlarski et al., 2015).

Those pollutions are exacerbated by edge effects. The study by Soga et al (2013) examines the edge effects on carabid beetle assemblages in urban remnant forests. They found

that a higher number of individuals and species was observed only in large interior zones and patches with a relatively large area (Soga et al., 2013).

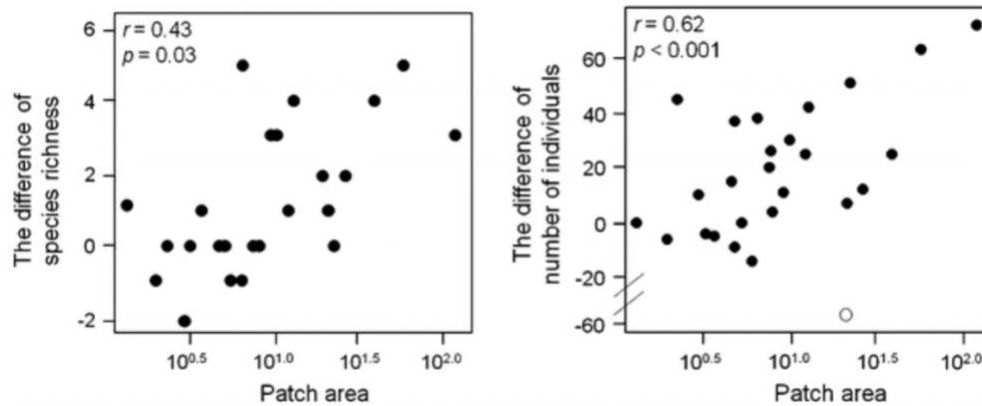


Figure 2 Correlation between patch area and carabid beetle species richness (left); patch area and number of individuals (right).

(Soga et al., 2013)

The two graphs above both display a statistically significant, positive correlation between patch area and species diversity in beetles. They show that insect biodiversity tends to decrease with the size of its habitat patches (i.e., the degree of habitat fragmentation). Therefore, habitat fragmentation exposes soil to more anthropogenic pollution and negatively impacts insect biodiversity significantly.

Urban Heat Island

Urban Heat Island effect is the phenomenon of urban temperatures significantly higher than those in surrounding rural areas, which can increase up to 12°C (Oke, 1973). With the warming of urban soils, the abundance of several insect groups such as herbivores, natural enemies, bees, and phorid flies decreases directly (Raupp et al., 2010). This is not only due to the shift away from the optimal temperature for those insects but is also due to the alter of soil

microbial communities. High temperatures can stress certain insects, such as ants and bees, and those with limited thermal tolerance; changes in the microbes prevalent in certain soils can damage soil fertility and structure (Tresch et al., 2019). Higher soil temperature can also reduce moisture retention of soils, making them drier and thus less hospitable for many insects (Raupp et al., 2010).

It is worth noting that, although urban heat island effect overall decreases insect biodiversity, the diversity for urban pests grows (Raupp et al., 2010). This is because they are more tolerant of extreme environments, and thrive when their predators, most of which are insects that are intolerant of high temperature, decline in population. Urban pests, such as scale insects and lace bugs, have shown increased diversity as temperature rises, which is linked to faster development rates and shorter periods of exposure to natural enemies (Raupp et al., 2010). Overall, urban heat island effect still causes a decline in soil insect biodiversity.

5. Case Studies of Urban Soil Systems and Management Strategies

Building on insect-soil interactions and the impact of urbanization on them, this section explores the change in soil environments along an urban to rural gradient, allowing comparison and shedding light on soil management strategies to conserve insect biodiversity.

Soil Insect Biodiversity along an Urbanization Gradient

The study by Ahrné, et al. (2009) examines the diversity of Bumble Bees along a Gradient of Increasing Urbanization. It was a field study conducted in Stockholm, Sweden's largest urban area. They examined allotment gardens, a type of intensively managed flower-rich

green areas, along a gradient of urbanization (Ahrné, et al., 2009). The results (see Fig. 3) show that as the degree of urbanization increases, bee diversity decreases. The study also indicates that green spaces close to rural areas have higher soil moisture level, organic content, and mineral content (Ahrné, et al., 2009). These contribute to an insect community with higher biodiversity and a stable soil ecosystem overall.

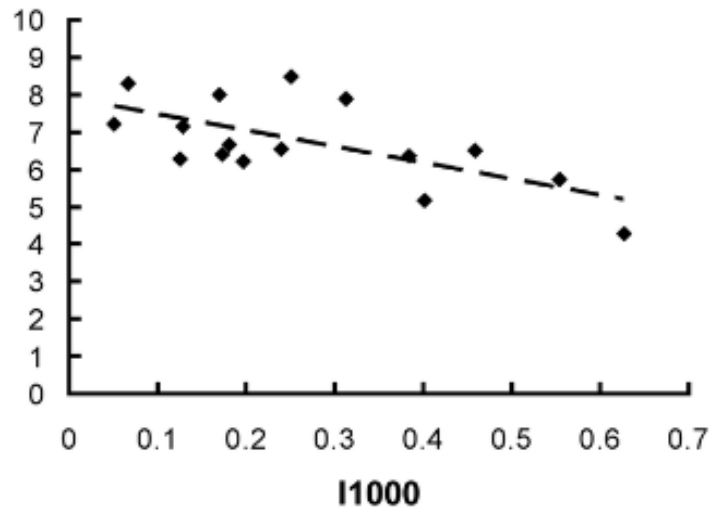


Figure 3 The relationship between number of bumble bee species (y-axis) and proportion of impervious surface within 1000m (x-axis). (Ahrné, et al., 2009)

Similarly, the study by Moreira et al. (2025) examines insect biodiversity on the edge of Brazilian Atlantic Forest, along an urbanization gradient, studying the overall insect family diversity. It reveals similar findings, showing that urban and human disturbance negatively impact insect biodiversity. As shown in Fig. 4, insect family diversity declines in peridomicile compared to forests, which is likely caused by soil compaction from human activities like grazing and impervious surfaces, leading to a reduction in soil air spaces (Moreira et al., 2025).

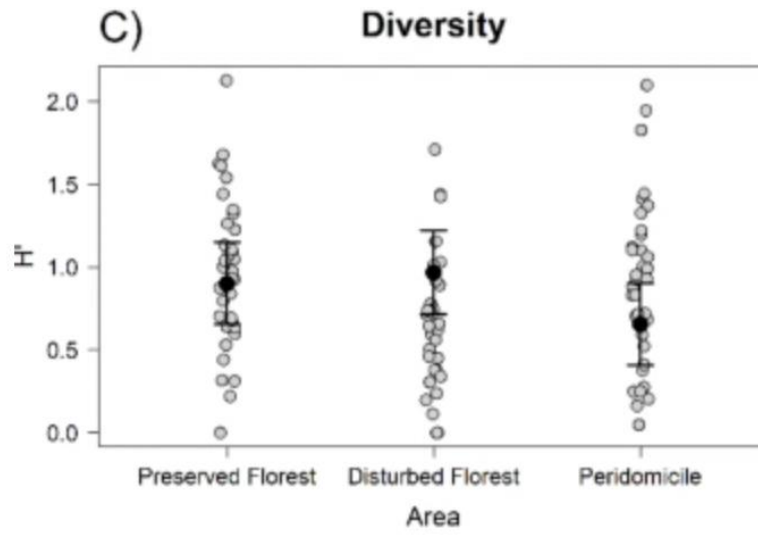


Figure 4 Comparison of insect family diversity in preserved forest, disturbed forest, and peridomicile (land used by locals for grazing)

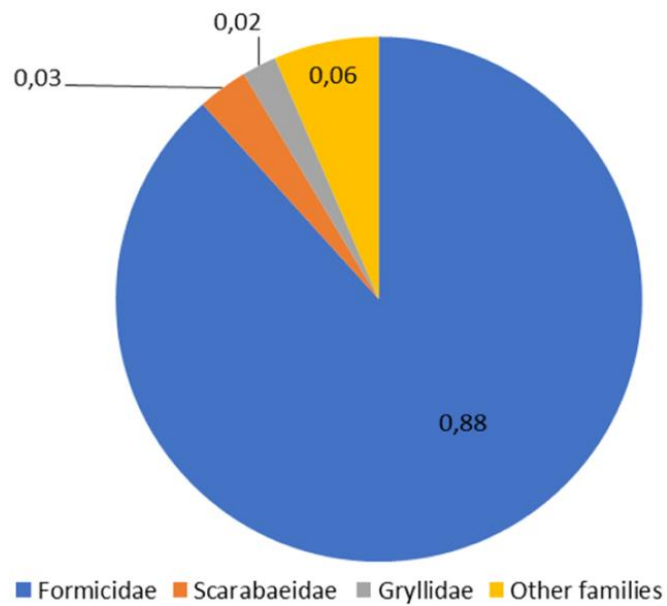


Figure 5 Relative frequencies of different insect families in the peridomicile

A notable finding is the significant presence of the Formicidae family in peridomicile (see Fig. 5). Formicidae includes many invasive species to the Brazil Fiocruz Atlantic Forest, including red imported fire ants, Argentine ants, and carpenter ants (Moreira et al., 2025). This is primarily due to deforestation, which creates additional microhabitats, such as fallen or cut tree trunks, that allow the establishment of invasive species populations (Moreira et al., 2025). This finding also aligns with discussion in the previous section of this paper, especially how urbanization reduces insect biodiversity overall, but increases the diversity of pests or unwanted insect species.

Urban Soil Management Strategies

Management strategies can be improved in three aspects: sustainable urban design, restoration, and monitoring (Fenoglio, 2021). Revegetation, especially accompanied by well-aerated, organic soil and native vegetation, can be effective for preserving native rare insects (Carpio et al., 2019). Also, monitoring soil indices that are important to insects, such as temperature, humidity, and pH, can help discover soil health problems earlier, but this strategy is most effective when implemented in conservation zones (Fenoglio, 2021). Moreover, based on the discussion on habitat fragmentation, healthy soil patches in a circular shape can minimize with limited exposure to edge effects (Soga et al., 2013), so this can also be a strategy when designing urban green spaces with soil. Green infrastructures such as green roofs and green walls can support higher diversity than traditional urban green spaces, because pollutants are less likely to reach those soils (Filazzola et al., 2019).

6. Conclusion

In conclusion, well-aerated and organic-rich soils tend to support higher insect biodiversity; urban environments tend to have lower insect biodiversity overall but exhibit an increase in the diversity of pests or locally unwanted insect species.

Understanding soil structure's impact on insect biodiversity is significant for soil and insect conservation and sustainable urban planning. The management strategies discussed in this paper can be applied not only at local sites but also on national and global scales. As climate change is increasingly impacting global ecosystems, especially with its disproportionately large impact on insects (McDonnell & Hahs, 2013), this paper sheds light on potential solutions to mitigate impacts on insects and their habitats. Conserving insect biodiversity is not just an environmental necessity—it stabilizes soil ecosystems through its interdependencies and feedback loops connecting pedosphere, biosphere, and climate.

Personally, I realize that despite their critical ecological roles, soil and insects are often overlooked by the public due to their tiny sizes and lack of eye-catching traits. Yet, they have immense potential in combating environmental challenges and improving environmental resilience. Future urban developments, along with related disciplines such as urban planning and landscape architecture, should consider soil and insect welfare more, recognizing them as fundamental components of a sustainable and resilient environment.

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