Review Article

Tiny Architects of Fertile Soils: Understanding the Role of Soil Arthropods

Abstract

Soil Arthropods are a vitally important component of the ecosystem, as their diversity, abundance, and distribution pattern play a vital role in ecosystem sustainability. Soil arthropods are critical to maintaining soil fertility and ecosystem health by driving essential ecological processes such as nutrient cycling, decomposition, and soil structure formation. As decomposers, these organisms, including mites, springtails, isopods, termites, and others, break down organic matter, aiding in the recycling of key nutrients like nitrogen and phosphorus, vital for plant growth. By burrowing and tunnelling, arthropods improve soil aeration, water infiltration, and aggregation, contributing to soil stability and resistance to erosion. Despite their small size, soil arthropods are essential ecosystem engineers, influencing the dynamics of microbial communities and facilitating the conversion of organic material into accessible forms for other organisms. However, their populations face threats from land-use changes, unsustainable agricultural practices, and the introduction of invasive species, all of which degrade soil health. Conservation strategies focused on habitat restoration, sustainable farming, and public awareness are crucial to protecting these vital organisms and ensuring the long-term sustainability of soils. A greater understanding of the roles played by these often-overlooked organisms can enhance conservation efforts and foster more sustainable agricultural practices, thereby supporting global ecosystem health.

Keywords: Arthropods, ecosystems, soil fertility

2. Introduction

Soils represent the fundamental organizing units within terrestrial ecosystems and harbor an exceptionally diverse array of prokaryotic and eukaryotic organisms. They exhibit substantial physical and chemical complexity, characterized by the presence of micro- and macro-aggregates integrated within a dynamic matrix of solid, liquid, and gaseous phases that is perpetually influenced by both natural and anthropogenic disturbances [1]. Soils are integral parts of ecosystems, and are maintained in a fertile state largely through the actions of their constituent biota[2]. The most dominant groups of soil organisms are microorganisms, such as bacteria and fungi, followed by a huge variety of animals such as nematodes, arthropods, enchytraeids, and earthworms [3]. Within the soil ecosystem, these microorganisms play pivotal roles in the breakdown of organic matter, the facilitation of nutrient cycling, the improvement of soil structure, and the regulation of soil biota, encompassing agricultural pests [4]. Moreover, soil organisms constitute essential elements within the intricate networks of soil food webs[5].

Soil arthropods constitute a fundamental element of soil communities and are instrumental in preserving soil integrity and vitality while contributing to the array of ecosystem services. It is widely acknowledged that soil arthropods participate in numerous ecological processes, including the translocation of organic matter, the fragmentation and decomposition of organic materials, nutrient cycling, the formation of soil structure, and, as a result, the regulation of water dynamics[6].

Soil is often seen as a static foundation, yet it is a dynamic and complex ecosystem teaming with life. Among the myriad organisms contributing to its fertility, soil arthropods stand out as crucial engineers. These tiny, often overlooked creaturesranging from mites and springtails to beetles and antsplay a vital role in breaking down organic matter, enhancing nutrient cycling, and promoting soil structure. Their activities are integral to maintaining healthy and productive soils, which are essential for agriculture, forestry, and natural ecosystems. By delving into the fascinating world of soil arthropods, we can better understand their contributions to ecosystem functioning and the sustainability of life aboveground.

2. Soil arthropods

Soil arthropods are invertebrates, possess jointed appendages, exhibit a range of sizes from microscopic to considerably large, and perform various ecological roles within the soil ecosystem. According to the classification based on body width, soil arthropods are categorized as mesofauna and macrofauna. They may also be referred to as microarthropods (0.2–2 mm) or macroarthropods (greater than 2 mm). In accordance with conventional taxonomic frameworks, soil arthropods fall under class Insecta (including Protura, Diplura, Collembola, and larger insects), class Myriapoda (Symphyla and Pauropoda), class Crustacea (Tardigrada, Copepoda, and Isopoda), and class Arachnida (Pseudoscorpiones, Araneae, and Acari)[7].Soil microarthropods represent a significant element within terrestrial ecosystems, primarily functioning as key regulators of essential processes such as the decomposition of plant litter and the mineralization of nutrients. The majority of microarthropods, typically categorized as saprophagic, may also exhibit omnivorous feeding behaviours[8].Among soil microarthropods, the taxa collembola and acari represent the two most significant groups with regard to their abundance and diversity [9], and they are also the most extensively studied taxa. These groups are frequently examined at various taxonomic levels, including family, genus, or species, while an alternative non-taxonomic approach emphasizes the investigation of functional groups or functional traits[10]. Additional microarthropod taxa that are commonly utilized to assess soil quality include: (i) insects such as adult and larval Coleoptera, Hymenoptera (particularly ants), and Dipteran larvae, (ii) Araneae, and (iii) Isopoda. Nevertheless, other taxa, including proturan, diplura, pseudoscorpionida, symphyla, and pauropoda, have received limited attention in research, and when they are studied, they are typically approached from a genetic, taxonomic, or ecological perspective [11] rather than being evaluated as indicators of soil health.Soil macroarthropods like earthworm, centipedes, millipedes, ground beetles, termites, spiders and others play important roles in soil ecosystem. Here some commonly found soil microarthropods and macroarthropods are mentioned below (Fig. 1).

Springtails (Collembola): classified as apterous insects, possess a segmented body measuring between 0.2 and 6 mm and exhibit specialized appendages, notably a spring-like furcula utilized for leaping. The majority of species inhabit soil or litter environments, whereas only a select few species reside on the surface or within the vegetation, predominantly belonging to the families Entomobryidae and Symphypleona. Collembola are recognised as for their reliance on the interplay between organic matter and humidity, exhibiting sensitivity to environmental disturbances[12].These also play an important role in decomposition of organic remnants and possess the ability to fragment and mill plant debris, thereby enhancing the establishment of microflora[13].

Acari: Mites are potentially powerful indicators, of the ecosystem nature as well as its disturbance[14]. This statement is based on their abundance, because they reach several hundreds of thousands of individuals per square meter.The Acari present in the soil ecosystem includes members that derive sustenance from decomposed plant matter and microflora (including bacteria and fungi). Furthermore, members of the Prostigmata and Mesostigmata orders exhibit predatory behaviour towards micro- and mesofauna, such as nematodes, collembolans, and enchytraeid worms. Oribatid mites have similar ecological functions as Collembola; they are agents of organic matter decomposition and consequently are important in nutrient recycling[15].

Protura and Diplura are also apterous insects. Owing to their distinctive morphological attributes like, a soft, diminutive, and chitin less body and their ecological roles (including detritivore, fungivore, phytophagy or herbivory, as well as predation), these are recognized as indicators of soil stability[16]. Protura prefer organic soils and feed by sucking on the outer layer of fungal hyphae. The diplurans, classified into two distinct families (Campodeidae and Japygidae), exhibit predatory behaviour, preying upon tiny faunal organisms. Additionally, they engage in the scavenging of decomposed organic material, root systems, and related substrates [7].

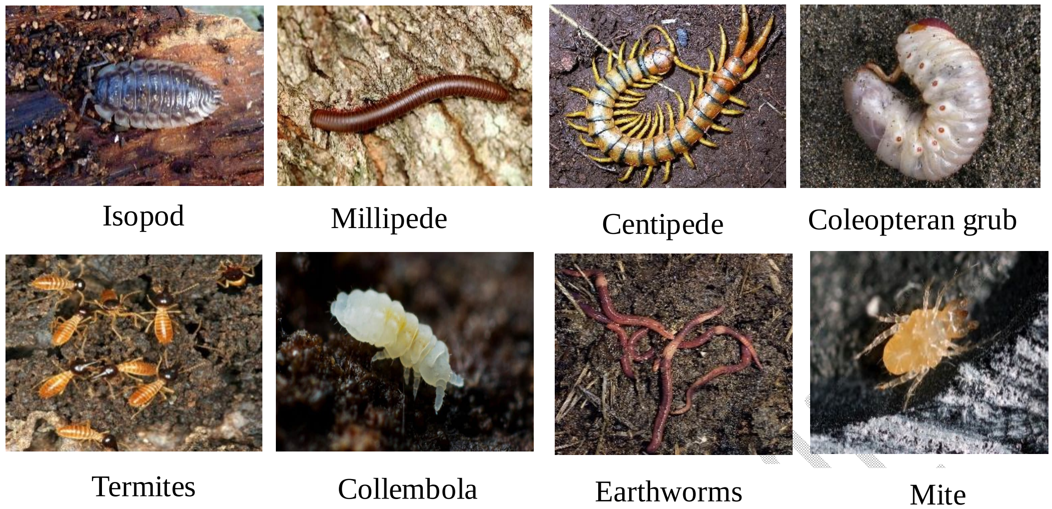
Isopods: The terrestrial isopods (Crustacea) also called as woodlice play an important role in the breakdown of litter and wood residues [17]feeding on which permits the recycling of essential nutrients, such as inorganic copper. Moreover, they have been used as bioindicators of soil quality and biodiversity to improve both agricultural production and environmental protection[18,19].

Millipedes (Diplopoda)and centipedes (Chilopoda):Chilopoda has been used in habitat quality indication [20]. Chilopoda are mostly generalist predators that are particularly prevalent in the soil and litter of forests and agroforestry systems [21]. In these environments, they perform crucial ecosystem services including regulation of decomposer population[22].Diplopoda is considered as ubiquitous taxon since it is present in almost all soils except in soils with lowest metal contamination [23].Since diplopods are detritivores, the vegetation structure is correlated with the makeup of their assemblages, species richness, and population density[24].

Isoptera (Termites):Termites are the more common insects in tropics and subtropics. These insects' dwell in small to big colonies and are eusocial and polymorphic. The colony is made of various castes; workers and soldiers with perfect division of labor, each with a body wall suited for their specific function[25]. Termites are known to be good bioindicators because of their wide geographic distribution, high abundance, taxonomic and ecological diversity, low locomotor capacity, functional significance, quick reaction to disturbances, sensitivity to environmental conditions, and ease of sampling and identification[26].

Coleoptera (Beetles): Coleoptera, the largest order of insectsisbeen widely used as indicators for their rapid response to habitat fragmentation, grazing, fertilization and forest cutting[27]. The majority of brown or black soil-dwelling beetle species reside in humus, leaf litter, decaying roots and logs, other rotting organic matter, dung, carrion, and the fruiting bodies of numerous types of fungi, where they greatly aid in the processes of decomposition. This is because of their wide variety of feeding habits[28].Many soil beetles, particularly species belongs to the family Carabidae, Leiodidae, Staphylinidae and Scarabaeidae are well adapted to the soil environment and have special habits[29].

Earthworm: Earthworm is an important organism to agriculture and it is called as "Nature's ploughman"[30]. Earthworms' burrowing and feeding activities have numerous beneficial implications on the general condition of the soil for crop production. The aeration, infiltration, structure, nutrient cycling, water movement, and plant growth of soil are all



enhanced by earthworms. One of the main organisms that break down organic debris is the earthworm[31].Earthworms seem to accelerate the mineralization as well as the turnover of soil organic matter. Earthworms are also known to increase nitrogen mineralization, through direct and indirect effects on the microbial community[32].

Fig. 1: Different arthropods in soil

3. Roles of soil arthropods in maintaining fertility of soil

Soils are essential components of ecosystems, and they are kept fertile largely due to the actions of their biota. Arthropods perform two primary roles in the soil system, they are ecosystem engineers and litter transformers.Litter transformers break down plant detritus, which improves the mineralisation of soil nutrients and promotes the rapid growth and dissemination of microorganisms. On the other hand, soil aggregates, void space, soil structure, and organic and mineral materials are all altered by ecosystem engineers.

3.1 Decomposition of organic matter

Soil arthropods, including mites, springtails,diplopoda, isopoda, acari and certain insect larvae, feed on decaying organic matter such as leaf litter, dead plants, and animals. This process helps break down large organic compounds into smaller, more accessible forms for microorganisms like bacteria and fungi, facilitating further decomposition.Arthropods are common decomposers in almost all land habitats, especially in temperate regions, playing a crucial role in waste degradation [33]. Nevertheless, cellulose and lignin, the two main plant components, cannot be readily broken down by arthropods. They establish a mutualistic relationship with the microbes in their digestive tract so that the cellulose and lignin can be broken down by an enzyme[34, 35].

3.2 Nutrient cycling

Nutrient cycling defines the flux of nutrients inside and between living and non-living components of the soil environment. It involves biological, geological, and chemical processes in the so-called biogeochemical cycles[36].Soil microarthropods play a significant part in the degradation of soil organic matter, mostly by mechanical action, prior to chemical breakdown by bacteria and fungi (both free and internal symbionts). In other words, they expedite the mineralisation process and render organic materials "tastier" to microorganisms. In addition to converting plant wastes into forms that microorganisms may more easily access, microarthropods also have an impact on soil porosity and, consequently, soil aeration through the creation of macropores [37].As soil arthropods consume organic matter, they release nutrients such as nitrogen, phosphorus, and potassium back into the soil through their waste products. These nutrients are essential for plant growth and contribute to soil fertility.Burrowing detritivores facilitate the translocation of nutrients from the pedological surface to subsurface layers through the decomposition of plant litter, as well as through their faecal matter and excretory products. The presence of animal burrows significantly ameliorates soil conditions by augmenting water infiltration, enhancing soil aeration, and providing thermal regulation, thereby establishing a conducive microenvironment for microbial communities and mesofaunal organisms, which in turn foster the mineralization of nutrients through the synergistic interactions of climatic variables and nutrient availability[31]. Increased environmental releases of calcium (Ca) and nitrogen (N) can result from collembolan feeding on fungus[38]. This phenomenon bears significant consequences for nutrient bioavailability, particularly in ecosystems characterized by acidic forest soils, where substantial nutrient reserves are typically sequestered within accumulated organic matter[2]. Arthropods that consume the microflora exert a regulatory influence on the rate of decomposition[39]. By doing so, it becomes easier to stop unexpected microbial blooms, which in turn makes nutrients more easily mineralised and freed from debris. As a result, in a steady and regulated manner, the nutrients become more easily absorbed by the plants, and their loss from the system is reduced to a minimum

3.2 Soil structure modification

The soil biota, especially the larger soil animals, contribute significantly to rates of soil turnover, soil texture and consistency, the formation of stable soil aggregates, total and macroporosity, the infiltration of water and soil water retention characteristics. Their activities, together with abiotic physical and chemical processes, regulate soil fertility and counteract physical and chemical processes of soil degradation [40-44]. The activities of soil fauna that significantly affect soil structure result from: i) the process of burrowing and excavation undertaken in search of food, or for the purpose of establishing living spaces or storage chambers either within the soil matrix or above the soil surfaceii) the active translocation of excavated or consumed soil materials and their subsequent deposition on the soil surface or within voids in the soil, or for the construction of nests or other structural formations iii) the consumption of soil materials, often with a preferential inclination towards plant litter or animal tissues iv) the utilization of excreta, mucus, or salivary secretions to line burrows or galleries, or as binding agents in the fabrication of construction materialsv) the gathering of plant litter, animal faeces, carrion, and similar organic matter from the surface, typically for nutritional purposes, and its subsequent integration into the soil with or without prior digestion.

Soil macroporosity is increased by earthworm burrows, with consequent enhancement of gas exchange, and water infiltration rates two to ten times faster than in similar soils that lack earthworms. Increased water infiltration through earthworm burrows leads to a reduction in surface runoff, with a decrease in soil loss by erosion, but is sometimes accompanied by an increase in downslope movement of fine textured materials from surface casts.Termites and ants are capable of drastically altering soil porosity, and many species of termite cement soils, in fabricating their nests and mounds, to form massive structures with little pore space [45].

Millipedes are the key groups involved in mixing organic matter with mineral soil [46]. Similarly, oribatids are believed to aid in the deep mixing of organic material by moving through the soil and depositing faeces in lower layers [47]. Symphyla, with their rapid vertical movements within the soil profile, also help disperse their faeces throughout the soil. These faecal materials are significant contributors to the formation of stable soil aggregates, which play a crucial role in maintaining proper water infiltration and drainage [48].

Soil aggregates, or peds, which are the fundamental components of soil structure, are formed through natural processes, often involving the actions of organisms [41, 49]. Invertebrates contribute significantly to soil aggregate formation through the production of faecal pellets that combine fine mineral particles with undigested organic matter [50, 51]. Mucilaginous substances, which are by-products of microbial decomposition, help bind these faecal pellets to other soil elements, creating stable microstructures [52,53]. The organomineralmicroaggregates formed from the faeces of soil-feeding termites are believed to contribute to the enhancement of structural stability and porosity in tropical soils.

4. Threats to soil arthropods and soil health

A majority of anthropogenic activities lead to soil degradation, which negatively affects the benefits provided by soil biodiversity.The depletion of soil organic matter and the phenomenon of soil erosion are exacerbated by suboptimal agricultural practices, excessive grazing, deforestation, and the occurrence of wildfires. The decrease in soil organic matter has a direct impact on the activity and diversity of soil organisms, whereas the decline in plant production and diversity has an indirect effect [54].

Land use change, due in particular to agriculture intensification, has been recognised as a major driver for biodiversity loss[55, 56]. The traditional agricultural practices, with ploughing, intensive crops and use of chemicals, have influenced abundances and diversity of edaphic communities [57-61]. Traditional ploughing (up to more than 30-40 cm deep) generally alters soil structure and buries crop residues resuming soils to the early stages of ecological succession [62,58]. Biodiversity decreases both within soil fauna taxonomic groups and among functional groups [63]. The communities under traditional agriculture are simplified with the reduction or the disappearance of some taxa, especially the most adapted to the soil and thus more sensitive to disturbances, and the predominance of these taxa that are more resistant. The population often needs decades to recover after tillage [64, 65].The increasing awareness of the importance of soils and their inhabitants, and the necessity of saving natural resources facing global changes have been reflected in the purposes of maintaining the functionality of agro-ecosystems and protecting habitats integrity [66, 67].Identifying sustainable methods for food production has become a pressing concern, and conservation agriculture is now widely acknowledged as an effective solution to address this issue[68].

As a consequence of globalization, invasive species have emerged as a significant threat to the biodiversity of soil ecosystems. Species classified as exotic are designated as invasive when their populations become disproportionately large. Invasive species can exert substantial direct and indirect effects on soil ecosystem services and the biodiversity of native species. The presence of invasive plant species can modify nutrient cycling, thereby influencing the population dynamics of microbial species within the soil, particularly those that exhibit specific ecological dependencies (e.g., mycorrhizal fungi). Populations of biological regulators are often diminished by the encroachment of invasive species, particularly when such species have specific interrelationships with plant communities. Soil biodiversity may function as a reservoir of natural enemies to invasive plant species. The establishment of biological control initiatives has the potential to conserve billions of rupees in the prevention and management of invasive species [69].

5. Conservation strategies

Nearly 98% of Earth's biodiversity exists within terrestrial ecosystems, with soil serving as the primary element, making the preservation of soil and its components, such as arthropods, crucial. It is imperative to plant trees on soils in tropical regions that are prone to erosion, compaction, and oxidation. Research from temperate areas has demonstrated that planting wildflower seed mixtures can greatly benefit insects (Samway 1994) and other arthropods. In tropical regions, managing human populations, establishing plant refuges with native species, restoring wetlands and water bodies, using pesticides and chemicals wisely, and preventing the overexploitation of natural resources are vital for habitat restoration. Limiting large-scale landscape alterations and reducing the development and destruction of fertile soils are essential for the conservation of arthropods. Captive breeding programs may help protect some endangered soil arthropods. Sustainable resource use should be the foundation of soil restoration ecology, with the ideal goal being the preservation of as many natural landscapes as possible. Due to their small size and unappealing appearance, arthropods are often undervalued in conservation efforts, and public awareness of these creatures is limited. However, the landscapes they inhabit should be protected or sustainably managed, as these arthropods play a crucial role in ecosystems.

6. Conclusion

Soils are essential components of ecosystems and their fertility is primarily sustained by the activities of the organisms within them. A soil's fertility depends on its ability to supply plants with necessary nutrients for growth and reproduction, as well as providing a physical structure that supports root development, respiration, and resistance to erosion. Arthropods play a key role in influencing soil fertility through two main mechanisms. First, they promote the decomposition of plant litter directly, by converting it into their own tissues, and indirectly, by transforming it physically and chemically into substrates amenable to further degradation.Soil arthropods are vital yet often overlooked contributors to maintaining soil fertility and ecosystem health. Through their activities, such as decomposing organic matter, recycling nutrients, and enhancing soil structure through tunnelling and burrowing, these small organisms play an indispensable role in the soil's ability to support plant growth and sustain biodiversity. Termites, collembola, myriapods, isopods, and other arthropods directly and indirectly influence the decomposition process, conditioning organic materials for further microbial breakdown and ensuring efficient nutrient cycling. Their efforts not only improve soil aeration and water retention but also strengthen soil's resilience to erosion. Recognizing the importance of soil arthropods is critical to conservation efforts and sustainable agricultural practices, underscoring the need to protect and preserve the ecosystems they inhabit. By valuing these tiny architects, we can better understand their integral role in soil fertility and ensure the long-term health of our planet's ecosystems.

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1. Quillbot (for paraphrasing)

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