Soil Biodiversity and Arthropods: Role in Soil Fertility

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Abstract

Healthy productive soils are essential to meet the food requirement of humans and animals. Arthropods have important role in maintaining soil fertility. The major contribution of arthropods to soil is through decomposition and humification of all organic matter. In the soil, arthropods function as litter transformers, ecosystem engineers, and pulverizers. As much as 20 % of total animal litter input is processed by the activity of collembolans alone. Arthropods also stimulate mineralization of nutrients in soil. Soil practices in cultivated ecosystems significantly alter arthropod community which in turn has significant effect on soil productivity. Arthropods facilitate soil processes. Hence, understanding soil arthropod communities will prove useful in developing management plans for both wild and cultivated ecosystems.

Keywords

Decomposition • Soil arthropods • Soil biodiversity • Soil fertility

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2.1 Introduction

The living organisms in soil range from microorganisms, small and large invertebrates to small mammals. Arthropods represent as much as 85 % of the soil fauna in species richness. They comprise a large proportion of the meso- and macrofauna of the soil. Macrofauna contribute to improve soil structure, aeration, and water infiltration. They predate on soil organisms and help to maintain biological equilibrium in soil. Mesofauna are important plant pathogens. Microfauna are important predators of bacteria and algae, thus regulating their population in soil. Arthropods function on two of the three broad levels of organization of the soil food web: they are plant litter transformers or ecosystem engineers. Litter transformers fragment, or comminute, and humidify ingested plant debris, which is deposited in feces for further decomposition by microorganisms, and foster the growth and dispersal of microbial populations. Large quantities of annual litter input may be processed, thus, for example, up to 60 % by termites. The comminuted plant matter in feces presents an increased surface area attack by microorganisms, which, through the process of mineralization, convert organic nutrients into simpler, inorganic compounds easily available to plants. Ecosystem engineers alter soil structure, mineral and organic matter composition, and hydrology. The burrowing by arthropods, particularly the subterranean network of tunnels and galleries that comprise termite and ant nests, improves soil porosity providing adequate aeration and water-holding capacity belowground, facilitates root penetration, and prevents surface crusting and erosion of topsoil. Also, the movement of particles from lower horizons to the surface by ants and termites aids in mixing the organic and mineral fractions of the soil. The feces of arthropods are the basis for the formation of soil aggregates and humus, which physically stabilize the soil and increase its capacity to store nutrients. Soil organisms are also responsible for many services like nutrient cycling, control of pests and diseases, formation of soil, degradation of wastes and harmful chemicals, and production of useful by-products like food, fuel, fiber, etc. In recent years industrial microbiologists have started looking into the soil for organisms capable of producing antibiotics, vitamins, hormones, and enzymes. The results obtained so far have revolutionized the industry in many countries. The objective of this paper is to review the state of knowledge on soil arthropods and its relevance to soil fertility and sustainable land use.

2.2 Pedogenesis and Composition

A handful of soil contains some minerals, organic matter, air, water, and living biota. Soil is one of the fundamental components for supporting life on earth. Soils originate and accumulate in a sequence of events that mark the stages of ecological succession, the development of biotic communities. Soil formation, or pedogenesis, involves a set of physical, chemical, and biotic processes. The properties of soils arise from the interactions of five basic factors: parent material, topography, climate, biota, and time (Jenny 1980).

The living organisms in soil range from microorganisms, small and large invertebrates, and small mammals. One teaspoon of garden soil contains thousands of species, millions of individuals, and a hundred meters of fungal networks. Bacterial biomass is particularly impressive and can amount to 1–2 t/ha which is roughly equivalent to the weight of one or two cows. Thus, for the soil biologists, soil is a living organism in an organic/mineral matrix. Soil biologists take two basic approaches for studying organisms: (i) taxonomic and (ii) process oriented (Bardgett et al. 2005; Gardi and Jeffrey 2009). Soil organisms have been classified on the basis of body width into microflora (1–100 μm, e.g., bacteria, fungi), microfauna (5–120 μm, e.g., protozoa, nematodes), mesofauna (80 μm^{-2} mm, e.g., Collembola, Acari), and macrofauna (500 μm–50 mm, e.g., earthworms, termites). The inventories of soil organisms have been considerably limited compared to above ground organisms, such as vascular plants. Another trend is that soil organisms of greater size (i.e., macrofauna) have received far greater attention than soil organisms of smaller size, despite greater diversity of the latter. The soil biota includes the macrofauna, mesofauna, microfauna, algae, fungi, prokaryotes, and rest of the microbiota, such as mycoplasmas, viruses, viroids, and prions (Turbe et al. 2010). Macrofauna include earthworms, mollusks, millipedes, earwigs, and insects. The major roles of macrofauna in soil are to accelerate organic matter breakdown and to mix organic matter and soil together. They contribute to improve soil structure, aeration, and water infiltration.

Biomass in soil means living organic material. While macrofauna may be big, they do not necessarily have the greater biomass in soil. The size and contribution to biomass are not necessarily related; neither are population density and importance to biological activity in soil. For example, two earthworms may have more effect on soil than a billion protozoa. Arthropods have long been recognized as important in the functioning of soil ecosystems, and a vast literature accordingly has accumulated, and principal roles played by arthropods in the processes that maintain soil fertility have been reviewed exhaustively (Culliney 2013).

2.3 Functional Grouping of Soil Biodiversity

Organisms found in soil can be categorized into three broad functional groups, viz., chemical engineers, biological regulators, and ecosystem engineers. Most of the species in soil are microorganisms such as bacteria, fungi, and protozoans, which are the chemical engineers of soil, responsible for the decomposition of plant organic matter into nutrients readily available for plants, animals, and humans (Gardi and Jeffrey 2009).

Soils also comprise a large variety of small invertebrates such as nematodes, pot worms, spring tails, and mites, which act as predators of plants, other invertebrates, or microorganisms, by regulating their dynamics in space and time. Most of these biological regulators are relatively unknown, contrary to the larger invertebrates, such as insects, earthworms, ants, termites, ground beetles, and small mammals, such as rats and mice, moles, and voles, which show fantastic adaptations to living in a dark below ground world. For instance, about 50,000 mite species are known to be soil living, but it has been estimated that up to 1 million species could be included in this group. Earthworms, ants, termites, and small mammals are also ecosystem engineers, since they modify or create habitats for smaller soil organisms. In this way, they also regulate the availability of resources for other soil organisms. Moles, for instance, are capable of extending their tunnel system by 30 cm per hour, and earthworms produce soil casts at rates of several hundreds of tonnes per ha each year (Barrios 2007).

Chemical engineers, biological regulators, and ecosystem engineers act mainly over distinct spatiotemporal scales, providing a clear framework for management options. This is because the size of organisms strongly determines their spatial aggregation patterns and dispersal distances. Thus, chemical engineers are typically influenced by local-scale factors, ranging from micrometers to meters and short-term processes, ranging from seconds to minutes (Brussaard et al. 2007).

2.4 Factors Influencing Soil Biodiversity

The activity and diversity of soil organisms are regulated by a hierarchy of abiotic and biotic factors. The main abiotic factors are climate, including temperature and moisture, soil texture and soil structure, and salinity and pH. Overall, climate influences the physiology of soil organisms, such that their activity and growth increase at higher temperature and soil moistures. As climatic conditions differ across the globe and at some places, between seasons, the climatic conditions to which soil organisms are exposed vary strongly. Soil organisms vary in their optimal temperature and moisture ranges, and this variation is life-stage specific, e.g., larvae may prefer other optima than adults. For instance, for spring tails, the optimum average temperature for survival is just above 20 °C, and the higher limit is around 50 °C, while some bacteria survive up to 100 °C in resistant forms. Soil texture and structure also strongly influence the activity of soil biota. For example, medium-textured loam and clay soils favor microbial and earthworm activity, whereas fine-textured sandy soils, with lower water retention potentials, are less favorable. Plants can strongly influence the activity and community composition of microorganisms in the vicinity of their roots, called the rhizosphere (Finlay 2006; Luster et al. 2009). In turn, plant growth may be limited or promoted by these soil microorganisms. Added to this, plants can influence the composition, abundance, and activity of regulators and ecosystem engineers, whereas these species in turn can influence vegetation composition and productivity. Finally, soil organisms induce plant defense responses to above ground pests and herbivores, and the above ground interactions can feed back in a variety of ways to the biodiversity, abundance, and activities of the soil organisms. In addition, within the soil food webs, each functional group can be controlled by bottom-up or top-down biotic interactions. Top-down effects are mainly driven by predation, grazing, and mutualist relationships. Bottom-up effects depend largely on competitive interactions for access to resources (Boellstorff 2008; Schils et al. 2008).

2.4.1 Organic Matter Decomposition

Organic compounds that reach the soil by way of animal and plant residues are made up of simple sugars, starch, cellulose, pectins, proteins, fats, waxes, lignin, phenols, tannins, alkaloids, pigments, and other products. The huge mass of the organic matter added to the soil is immediately acted upon by the soil biota (Bardgett et al. 2005):

- Macrofauna (millipedes, mollusks, wood lice, and fly larvae) attack the litter. They puncture the leaf epidermis in a process called fenestration and open the leaf to microorganisms. Larger the material's surface area, the more available it is for microbial attacks. If you exclude macrofauna from soil, organic matter decomposition slows. An interesting experiment that showed this effect involved incubating leaf tissue in mesh bags that excluded different organisms based on size and burying the bags in soil. About 95 % decomposition occurred in the 7.0 mm mesh that did not exclude compared to 35 % decomposition in the 0.5 mm mesh that excluded all but the smallest invertebrates and microbes.
- Mollusks, wood lice (isopods), millipedes, earwigs, fly larvae, and earthworms macerate the leaf litter and pulverize it.
- Earthworms, insects, and other burrowing creatures transport the litter into soil.
- Earthworms and pot worms further macerate the litter and mix it with soil.
- Microbial action turns the litter into an integrated component of the soil.

2.4.2 Symbiotic Nitrogen Fixation

Nitrogen is one of the major elements required for crop production. Nitrogen is present to the extent of 80 % in the atmosphere. Field trials in India have shown that rhizobial inoculation can increase yield of grain legumes by 20–50 % (Bagyaraj 2011).

2.4.3 Nonsymbiotic Nitrogen Fixation

A number of free-living organisms inhabiting soil are capable of fixing atmospheric nitrogen. Bacteria of genera *Azotobacter*, *Beijerinckia*, *Derxia*, and cyanobacteria (blue-green algae) are well known among these. Besides the ability to fix atmospheric nitrogen, *Azotobacter* is also known to synthesize biologically active substances such as B-vitamins, IAA, and gibberellins (Bengtsson et al. 2005).

2.4.4 Phosphorus Mobilization

Although a soil may have adequate quantities of phosphorus, it may be present in bound form unavailable to plants. Many fungi and bacteria (like *Aspergillus*, *Penicillium*, and *Bacillus*) are potential solubilizers of bound phosphates as revealed by experiments in pure culture. These organisms produce organic acids like citric, succinic, lactic, and oxalic acids responsible for the solubilization of insoluble forms of phosphorus. A commercial preparation called "Phosphobacterin" containing *B. megaterium* has become popular. Another area attracting the attention of soil biologists is mycorrhiza. In nature the roots of most plants are invaded by fungi and are transformed into mycorrhiza which means "fungus root." The host and the fungus live in intimate symbiotic relationship. The fungi help in the phosphorus nutrition of plants through increased surface area of absorption, offer protection against moisture stress and some of the soil-borne plant pathogens, and enhance rooting and survival of cuttings through production of growth hormones (Bagyaraj 2014).

2.4.5 Biocontrol of Plant Pathogens

Eco-friendly organic farming technologies for plant protection have been gaining importance in recent years. Some of the plant diseases that can be controlled by antagonistic fungi and bacteria are as follows: rice seeds treated with *Pseudomonas aeruginosa* and *P. putida* reduced sheath blight infection (*Rhizoctonia solani*) in rice by 65–72 % in comparison to untreated check; *Pseudomonas fluorescens* was also found effective against banded leaf and sheath blight fungus (*R. solani* f. sp. *sasakii*). *Trichoderma harzianum* as fungal antagonist proved effective against *Macrophomina phaseolina* (charcoal rot) in several plant species (Powlson et al. 2012).

2.4.6 Pesticide Degradation

Degradation of pesticides in soil, by soil microorganisms, is another area of research in which scientists are actively engaged today. Some pesticides can be used as carbon and energy substrates by microorganisms and thus result in the disintegration of the pesticide (Powlson et al. 2012).

2.4.7 Extension to Other Fields

In recent years industrial microbiologists have started looking into the soil for organisms capable of producing substances including antibiotics, vitamins, hormones, and enzymes. The results obtained have revolutionized the industry in many countries. Several actinomycetes and some fungi and bacteria have been used in the industry for the production of antibiotics. *Torulopsis* spp. and *Ashbya gossypii* produce thiamin and *Streptomyces olivaceus* and *Streptomyces griseus* produce vitamin B_{12} in the fermentation broth. *Gibberella fujikuroi* has been utilized for the production of the plant hormone, gibberellic acid. Commercial proteolytic enzymes are produced using the soil fungus *Mortierella* spp. (Constanza et al. 1997).

2.5 Economic Value of Soil Biodiversity

In order to allow for performing cost-benefit analyses for measures to protect soil biodiversity, some economic estimates of the ecosystem services delivered by soil biodiversity need to be provided. Several approaches exist. The valuation can be based on the prices of the final products, such as food, fibers, or raw materials, or be based on the stated or revealed preference. The stated preference methods rely on survey approaches permitting people to express their willingness to pay for the services provided by biodiversity and its general contribution to the quality of life (e.g., aesthetical and cultural value). Alternatively, cost-based methods can be used; the value of a service provided by biodiversity is evaluated through a surrogate product. Thus, the "damage avoided" cost can be estimated, for instance, by the amount of money that should be spent to repair the adverse impacts arising in the absence of a functioning ecosystem (e.g., in the case of soil biodiversity, the cost of avoided floods). It has been estimated by economists that the world economic benefit of soil biodiversity is to the tune of several billion US dollars per year. For example, for waste recycling, it is 760×10^9 USD/year, soil formation 25×10^9 USD/year, nitrogen fixation 90×10^9 USD/year, degradation of chemicals 121×10^9 USD/year, pest control 160×10^9 USD/year, pollination 200×10^9 USD/year, etc. (Pimentel 1997; Barrios 2007; Brauman et al. 2007).

2.5.1 Soil Arthropods

Soils may harbor an enormous number of arthropod species. By one estimate, the soil fauna may represent as much as 23 % of all described organisms, with arthropods comprising 85 % of that number (Decaens et al. 2006). However, accurate figures have been difficult to come by, hampered, at least in part, by limitations in sampling methodology (Stork and Eggleton 1992). Arthropods comprise a large proportion of the meso- and macrofauna of the soil, animals with body lengths ranging from about 200 μm to 16 cm or more (Wallwork 1970). Of the hemiedaphon and euedaphon, those organisms live within the litter/humus boundary and lower in the soil profile (Eisenbeis and Wichard 1987).

2.5.1.1 Nematodes

One handful of soil from almost any area, among other forms of life, possesses elongate, threadlike, active animals which include the nematodes and other related forms. The word nematode is derived from the Greek root "NEMA" meaning thread. It is probably one of the oldest existing life forms on the basis of the fossil specimens discovered in Scotland (Maggenti 1981).

Based on their habitat, nematodes can be grouped into marine, soil, and freshwater forms. The marine nematodes form the largest group, about 50 % of the known nematode population. Soil nematodes, including the free-living, plant and animal parasitic, form the remaining 50 % of the total nematode species. The free-living forms have a variety of food habits. Some are predacious on soil microfauna including nematodes. Others use algae, fungi, and bacteria as their food source.

Nematode body is usually cylindrical to fusiform, tapering toward either end and somewhat wide in the middle. The females of some genera like *Heterodera* and *Meloidogyne*, however, may be spherical or oval. The soil and phyto nematodes may be 0.5–12 mm long and 20–30 μm wide. While the body is usually transparent, some may be, and rarely so, whitish or yellowish. Other colors may be due to the color of the ingested food. Externally the body is covered by a transparent, tough, cuticle invaginated at body openings such as oral, anal, excretory, and vaginal. In cross section, the body is more or less circular with its surface exhibiting pseudo segmentation on account of in folding of the cuticle. The nematode body is generally bilaterally symmetrical.

Organic matter is an essential component of all agricultural soils and influences the general microbial population of soil. Several hypotheses for the possible mechanisms involved in the management of nematodes have been put forth. One of these is that the products from decomposing organic matter are directly toxic. The second is that the microbivorous nematodes rapidly reproduce on the abundant bacteria and the decomposing products and help stimulate activity of natural decomposition involving changes in the soil. These changes promote host vigor by more efficient utilization of the soil nutrients (Sayre 1971).

There are countless microorganisms capable of decomposing plant and animal residues in soil. A succession of these microorganisms mediates a stepwise degradation of organic matter. The resulting products like fatty acids, enzymes, toxic gases (H_2S, NH_3), etc. have been found to be toxic, antibiotic, inhibitory, or attractive to nematodes.

Possibly the only but very interesting example of the influence of animal exudates is an odoriferous, volatile compound by the insect, *Scaptocoris talpa* Champ, protecting tomato seedlings from the attack of root-knot nematodes (Timonin 1961). Several plants (marigold, crucifers, asparagus, and citrus) have been demonstrated to have chemicals in their roots antagonistic to nematodes (Winoto Suatmadji 1969). The possibility of utilization of these agents in nematode management could materialize only when these principal chemicals in the exudates are characterized and their potential as nematicides explored.

The soil flora and fauna predacious on plant parasitic nematodes include fungi (*Arthrobotrys*, *Dactylaria*, *Dactylella*, *Catenaria*), other nematodes (*Diplogaster*, *Seinura*, *Mononchus*), Tardigrades (*Hypsibius myropus*) turbellarians (*Adenoplea* spp.), Collembola (*Isotoma* spp.), mites (*Onychiurus armatus*), enchytraeids, and protozoa (*Theratomyxa weberi*), whereas parasitic forms include viruses, some fungi (*Dactylella oviparasitica*), protozoa (*Duboscquia penetrans*), and bacteria (Barron 1977; Stirling and Mankau 1978).

Abiotic ecological factors influencing nematodes in soil environment include soil structure (particle size distribution, soil pores, and mechanical strength of soils), soil water (surface tension, suction, moisture characteristic, moisture profile, hysteresis, movement of water and osmotic potential), soil aeration, chemical properties of soil (soil reaction and soil chemicals), and soil temperature (Norton 1978).

2.5.1.2 Annelids

The terrestrial annelids are common earthworms, included under order Oligochaeta, the major soil fauna of the world. They have widespread distribution and show a high degree of adaptability to the prevailing soil conditions. Among the land inhabiting Oligochaeta, *Microdrili*, and other members belonging to terrestrial Enchytraeidae, are encountered in many habitats where true earthworms also occur.

2.5.1.3 Enchytraeids

The Enchytraeids differ from the lumbricids by their small size (5–15 mm) and whitish color. Overgaard Nielsen and Christensen (1959) have given the classification of Enchytraeids. They are mostly found in the top layer of somewhat moist, root-penetrated soil and in the litter of forests. They are absent in thick loamy soils having few pore space and in badly aerated wet soils. Their chief diet consists of dead plant residues. They can digest undecomposed plant residues but completely decomposed plant material is unsuitable. Occasionally Enchytraeids feed on pupae and eggs of insects and on small nematodes (Jegen 1920). Their distribution is mostly dependent on the type of soil.

2.5.1.4 Earthworms (Fig. 2.1)

Earthworms are considered as the most beneficial organisms to agriculture and are called "Nature's ploughman" (Darwin 1881). A large proportion of the energy of mature worms is used in cocoon production and the life span of the worms is directly related to the number of cocoons produced (Kale and Krishnamoorthy 1981). The size, shape, and color of the cocoons are species specific. The juveniles resemble the adults except in size. The time of attainment of reproductive phase varies in different species. Parthenogenesis in earthworms is recorded.

Earthworms are the major secondary decomposers in the soil (Fig. 2.1). The degradation of the leaf material commences from the time it detaches from the plant and drops to the ground to add to the litter. The worms feed upon litter materials partially degraded by microbes. Earthworms are found in association with other soil invertebrates like soil turbellarians, soil insects, and myriapods. Scarabaeid beetles, millipedes, centipedes, Turbellarians are considered as their natural enemies (Dindal 1970; Edwards and Lofty 1972).

2.5.1.5 Worm Cast Production and Physiochemical Properties of Soil

Worm casts are found in large amounts on soil surface during rainy season (Gates 1961; Dash and Patra 1979). Even in dry season, the dried-up crumbs of castings can easily be differentiated from the surrounding soil. The amount of casting produced on the soil surface is an index in assessing earthworm activity. The nature of worm cast is species specific. The earthworms that drill extensive burrows in the soil may use the casts with mucus to pack the walls of burrow. The castings of such burrow forming species are usually found on the burrow openings. *Pheretima posthuma* produces pellet-like casts and *Perionyx millardi*'s castings are threadlike.

Earthworms (Annelida)

Pseudo scorpion (source: arthurevans.wordpress.com)

Snail (Mollusca)

Termites

Fig. 2.1 Macroarthropods

Hoplochaetella khandalaensis produces thick and long winding column which will be a hollow mound of 5 cm long and 2.5 cm wide. The biggest recorded casting is that of *Notoscolex birmanicus* from Burma. The dry weight of one casting of this worm weighed 1.6 kg after drying for 4 months (Tembe and Dubash 1961). *Perionyx excavatus* which does not form definite burrows in soils leaves the castings as minute noodle-like structures. The castings of *Lampito mauritii* are fine granular mounds of soil. *Pontoscolex corethrurus* and *Pheretima elongata* excrete the ingested soil as sticky, thick lumps on soil surface. The castings of *P. excavatus* are completely on the surface, whereas *P. elongata* and *P. corethrurus* use part of their castings to farm the burrow lining.

Physical-chemical properties of the castings differ from soil to soil. The large tower like castings of *Eutypheous woltoni* had coarser fractions than the surrounding soil. Small-sized castings were found in the same region and were superior to large castings and also the parent soil in their rate of percolation and dispersion coefficient. The aggregate size also differed in these two castings. The chemical composition of both the castings was found more favorable to plant growth than surrounding soil.

The pH of the castings was found higher than the surrounding soil. Total nitrogen, organic matter, nitrate nitrogen, phosphorous, potassium, sodium, and magnesium were at a higher level in the castings than in rest of the soil (Kale and Krishnamoorthy 1979; Dash and Patra 1979). Earthworms utilize the organic matter as food and release part of carbon as Co_2 in the process of respiration. The production of mucus and nitrogenous excrements enhances the level of nitrogen, and this in turn leads to the lowering of C:N (Senapati et al. 1980). The differences observed in the oxidizable carbon and other minerals in the castings are mostly due to selective feeding habit of the worms. They selectively feed on the decomposing particulate matter and defecate the partially digested material into the soil surface with coating of mucus (Kale and Krishnamoothy 1980). The castings of *Pontoscolex corethrurus* were found rich in soluble calcium and carbonates. Soluble carbonates contribute to the exchangeable base content of the castings (Kale and Krishnamoorthy 1980).

Earthworms are considered as biological converters of chemicals. Patel and Patel (1959) observed the high susceptibility of earthworms to soapnut (*Sapindus laurifolius*) extract. In fields, the application of soapnut extract was most effective against earthworms. The survivability, activity, and fecundity of the worms are highly influenced by residue concentrations. The concentration of carbaryl up to 100 ppm was favorable for worms (Kale and Krishnamoorthy 1979). In New Zealand, the effective control of chafer grubs was brought about by earthworms in transferring the pesticides into lower soil layers (Edwards 1973).

2.5.1.6 Snails and Slugs (Fig. 2.1)

Snails and slugs are more or less similar in structure except that the slugs lack the external hard spherical protective shell and their mantle is smoother. The color of slugs varies from gray to black. Both withdraw their body into shell when disturbed.

About 80,000 species of snails and slugs are described from the phylum Mollusca and are distributed throughout the world, inhabiting aquatic (including marine and freshwater) and terrestrial ecosystems. They are herbivorous, carnivorous, and also fungivorous. In terrestrial habitats, they live mostly in sandy, moist, damp places and feed on vegetable matter either live or dead. They are soft-bodied, unsegmented animals having an anterior head, a ventral muscular foot, and a dorsal visceral mass. Their body is surrounded by a specialized fleshy area known as mantle characteristic to this group, which is sheltered within an external limy shell.

The pulmonate slugs and snails feed voraciously on plant material, preferring the more succulent parts. Some slugs, like *Limax* spp., feed on bulbs, tubers, or roots, while *Arion subfuscus* feeds on fungi. In certain species powerful cellulase brings about complete digestion of the plant tissues, assuming that carbohydrates, lipase, and proteases are still being retained. Armed with this digestive tool, slugs and snails are able to cut and ingest comparatively large pieces of leaf and feed rapidly.

Rate of growth and reproduction may be high, especially in the tropics. The Giant African Snail, *Achatina*, is particularly formidable as a phytophagous pest. The snail *Partula*, occurring in Pacific islands, apparently subsists exclusively on the mycelia of fungi that grow on decaying plant materials.

2.5.1.7 Microarthropods

Soil arthropods measuring up to 10 mm in length can be considered as microarthropods. They are also considered as members of the mesofauna of the soil. These include Protura, Diplura, and Collembola of the class Insecta, Symphyla and Pauropoda of the class Myriapoda, and Tardigrada, Copepoda, and Isopoda of the class Arachnida.

Tardigrada

Tardigrada are peculiar arthropods, with worthy surface, possessing four pairs of stumpy, claw-bearing legs; the snout is conical. They normally live in moss cushions, but active tardigrades have been recorded from meadow soils and leaf litters. Their food consists partly of organic residues and partly of the contents of moss cells. They are also known to feed on nematode. *Macrobiotus* sp. feeding on *Rotylenchulus reniformis* and *Aphelenchus avenae* has been reported from India (Narayana Swamy and Nanje Gowda 1980). Females lay thick-shelled eggs in their skin carts. These anabiotic eggs are resistant to desiccation and may be blown up till the moisture is available. Species of the genera *Macrobiotus* and *Lydella* commonly occur in the soil.

Terrestrial Isopoda

The terrestrial isopods called woodlice (Oniscoidea, crustacean) play an important role in the breakdown of litter and wood residues (Kunhelt 1976). More than 3500 species in 518 genera have been described (Schmalfuss 2003). Despite their diversity, these animals are imperfectly adapted to a terrestrial existence. In particular, a set of structural (e.g., permeable cuticle) and physiological (gills) traits little modified from a marine ancestor means that the maintenance of water balance is of paramount importance to survival and is largely achieved through behavioral means. Isopods attain their greatest abundance in unmanaged temperate grasslands, numbers typically ranging from about 500–1000 m^{-2} (Curry 1994). A density of 7900 m^{-2} was estimated for *Trichoniscus pusillus* Brandt in scrub grassland in Britain, the maximum ever recorded for an isopod species (Sutton 1980).

They abound in decaying wood. The abdominal legs are adopted for aerial respiration. Their endopodites bear delicate branchiae traversed by minute tubes called "pseudotrachea." They feed on a variety of dead and decaying matter. They do not have an epicuticular wax layer, and, therefore, moisture is an important limiting factor in their distribution. In evergreen forests where abundant moisture is available, even during dry periods, they may play an important role in the breakdown of litter. Members of the genera *Porcellio*, *Oniscus*, and *Armadillidium* are common in the soil.

2.5.1.8 Arachnida

Pseudoscorpions

Pseudoscorpions (Figs. 2.1 and 2.2) are small, predaceous arachnids preying on small arthropods, psocids, collembolans, and mites. They live in habitats like soil cover, beneath barks, bird nests, etc. in small numbers. They easily escape notice by withdrawing their legs and palps playing possum.

Pseudoscorpions display elaborate courtship. Normally the female pseudoscorpions build nests during brooding. The nest is constructed with silk secreted by the silk glands present in the chelicerae which come out through the galea. Some species dwelling in the soil like *Compsaditha indica* do not build nests, and the brood sacs are firmly attached to the underneath of their abdomen.

The eggs undergo development within the brood sac and the time taken for the same varies from 3 days (*Compsaditha indica*) to 21 days (*Stenatemnus indicus*). During the last instar, the young ones receive copious secretion from the ovary, rich in protein yolks. They suck this secretion with the pumping organs which would have developed by now and get themselves bloated up as small balloons. Soon the brood sac gives way and protonymphs emerge out. The number of eggs carried by the female varies from 4 to 24.

Soil Acari

The Acari (Fig. 2.3) of the soil includes members that feed on dead plant materials and microflora (bacteria, fungi). In addition, species of Prostigmata and Mesostigmata prey upon micro- and mesofauna (e.g., nematodes, collembolans, enchytraeid worms). The oribatids are the numerically dominant group of Acari.

Populations of oribatids in the order of 105–106 individuals m^{-2} have been recorded in different forest types (Petersen and Luxton 1982), with densities higher in coniferous than in deciduous soils (Wallwork 1983). In desert ecosystems, their numbers comparatively are much reduced (Wallwork 1982), and roles in the turnover of organic matter insignificant (Whitford et al. 1983). A major abiotic factor constraining the distribution of oribatids is adequate moisture. With more than 9000 species in 172 families, most of which inhabit the soil/litter system (Norton and Behan-Pelletier 2009), the oribatids are considered the most successful of all soil arthropods. Species tend to exhibit low metabolic rates, slow development, lengthy life cycles, low numerical response capability, generally stable population densities, low fecundity, and iteroparity (Norton 1994). These traits suggest *K*-selection and are probably influenced in part by the low nutritional quality of the diet. Parthenogenesis may be common.

On the basis of vertical stratification, three "life forms" of Acari can be recognized, viz., soil forms, wandering forms, and arboreal forms. Soil forms in contrast to the other two forms live restrictedly in soil environment in a wide sense. Although soil also serves as a shelter for ticks during their life span, these are not considered as soil forms. On the basis of habitat, soil forms may be further grouped into two categories: edaphic, which live in the deeper soil layer (e.g., *Epilohmannia*), and hemiedaphic, which are inhabitants of litter and upper soil layers (e.g., *Scheloribates*).

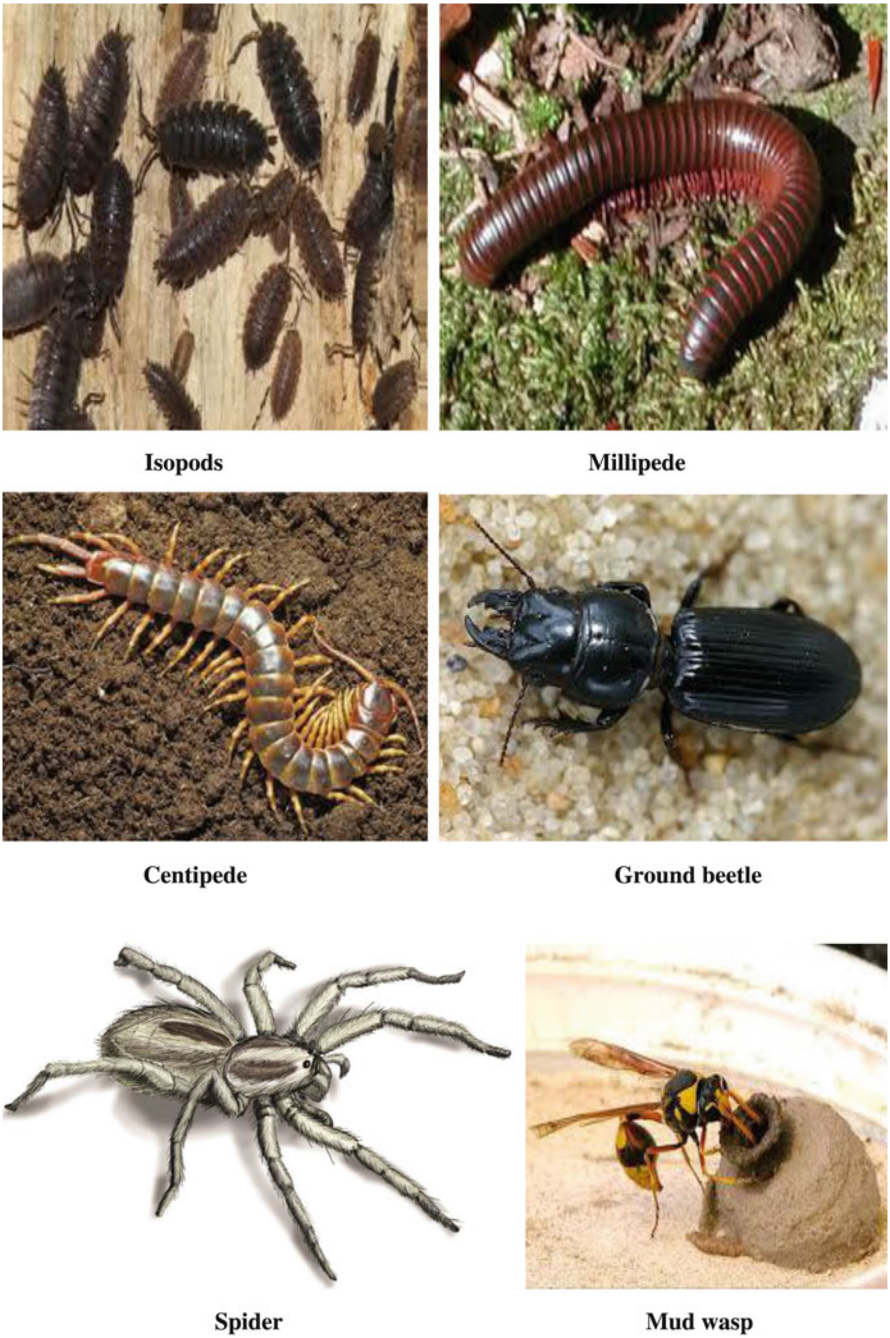

Fig. 2.2 Soil arthropods

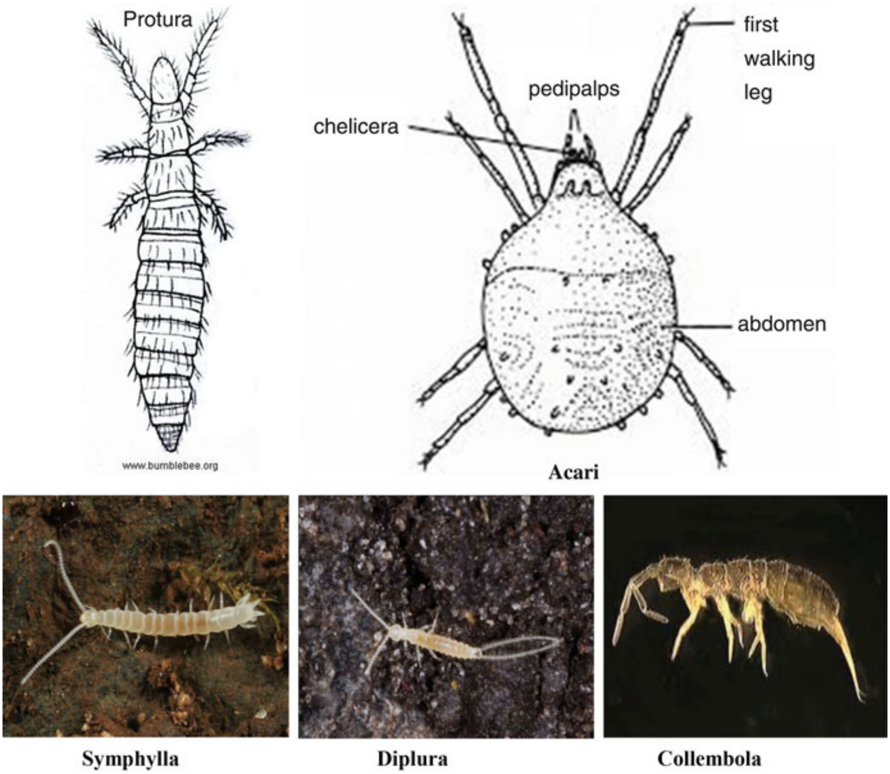

Fig. 2.3 Microarthropods

The feeding ecology of oribatids is diverse. Four main groups, based on modes of feeding, are commonly recognized: macrophytophages, which feed mainly on decaying higher plant material and rarely on fungi; microphytophages, those types feeding on fungi, bacteria, and other microflora; panphytophages, which have an expanded diet breadth, including plant matter as well as fungi; and coprophages, the diet of which includes fecal material. The majority of oribatids are obligate or facultative fungivores (Wallwork 1983). These animals have been contributing to the breakdown of plant litter since early in the Pennsylvanian Epoch of the Carboniferous period, perhaps 316 million years ago.

Symphyla

The Symphyla are small group of arthropods, with a reported 208 species in 13 genera and 2 families (Chapman 2009; Szucsich and Scheller 2011). Populations, however, may be large in some environments, in the order of 103–104 individuals / m^{-2}, and reach the highest densities in cultivated soils. Species also are common in grassland and forest soils. By one estimate, they may represent as much as 86 % of the total myriapod population in some soils, but are often overlooked because of their small size and wide dispersion through the soil profile.

Symphyla (Fig. 2.3) are whitish, slender, and eyeless microarthropods measuring 5 mm in length. Body has 12 segments and a telson. The last segment bears a pair of cerci or spinnerets but no legs. The group appears to reach its greatest diversity in warm temperate and tropical regions. About 12 species of Symphyla are reported from India. These animals are highly hygrotactic and survive only in a soil atmosphere of 100 % R.H. Symphyla are said to be extremely voracious and will attack vegetable matter at an earlier stage of decomposition than many other soil-inhabiting invertebrates (Edwards 1990). Some like *Scutigerella* and *Symphyllia* feed on fresh roots of plants. Scutigerellids consume decaying plant and animal matter.

Protura

The Protura, like the Pauropoda, are also minute creamy white and blind animals ranging in length from 0.5 to 1.5 mm (Fig. 2.3). They lack antenna. The abdomen has 12 segments and the first three segments ventrally bear rudimentary legs. About 20 species belonging to 9 genera and 3 families have been reported from India, especially from Kerala (Prabhoo 1972). Although they are more abundant in the forest soils, they are also common in grassland and plantation soils. They are apparently rare or absent in heavy soils. The Protura are known to feed on mycorrhizal fungi and for this reason they are likely to be more abundant in the feeder root zone of the plants.

Diplura

The Diplura (Fig. 2.3) are whitish, slender, blind insects reaching about one centimeter in length. The abdomen is ten segmented and ends in a pair of cerci. Ventrally on the abdomen segments 1(2)-7, coxal styli and bladders are present. Nine genera belonging to two families have been reported from India. *Japyx* is more widely distributed than *Anajapyx*, *Campodea* and *Heterojapyx* (Ghaisas and Ranade 1981). *Projapyx* is very rare. Both predatory and detritivorous forms are present under Diplura.

Collembola

The Collembola or the springtails are characterized by a six segmented abdomen bearing median appendages ventrally, i.e., ventral tube, the tenaculum, and the furcula (Fig. 2.3). The furcula and tenaculum may be reduced or absent in some families like Onychiuridae and Neanuridae. They formerly classified as primitively wingless insects (Boudreaux 1979), but now widely recognized as a lineage closely related to, but distinct from, the Insecta (Giribet and Edgecombe 2012). About 6500 species in 18 families have been described (Hopkin 1997). Like the oribatids, they also are extremely abundant in soil and leaf litter, with densities typically on the order of 104–105 individuals /m^{-2} and, again, higher in coniferous forests (Petersen and Luxton 1982), but are more numerous than oribatids in many soils. Agricultural soils may be rich in Collembola (Christiansen 1964). Edaphic species tend to be parthenogenetic (Hopkin 1997), life-history trait characteristic of animals living in stable environments. Average fecundity typically ranges between 50 and 100 eggs per female; depending on climate, there may be one to four generations annually.

Life spans of species living within the soil-litter system range between 2 and 12 months or more. Like soil-dwelling oribatids, Collembola require a soil atmosphere approaching saturation. The diet of Collembola is of considerable variation, including moss protonema, bacteria, fungal hyphae and spores, algae, protozoans, arthropod feces, pollen, decaying plant materials and humus, other Collembola (living or dead), and stored products. Species are divided between those that masticate their food and those that are fluid feeders. Majority of species are fungivorous (Hopkin 1997).

2.5.1.9 Millipedes and Centipedes

Diplopoda

Millipedes vary in body length from a few mm to 20 cm, with a minimum of 9 pairs of legs to a maximum of 200 pairs. Because of the wavelike motion of these legs, the animals appear to have thousand legs, hence their common name. About 12,000 species of millipede have been described and assigned to 2947 genera (Sierwald and Bond 2007). Millipedes are widely distributed; they are essentially the inhabitants of the forest floor (Blower 1951), with mull-type humus, and also are numerous in deciduous forests with a more humus formation. They tend to be more abundant and diverse in calcareous soils, in fairly moist habitats, and typically in the upper soil horizons. Densities of 1000–3000 /m^{-2} have been recorded. Individuals exhibit considerable longevity. Females of *Glomeris marginata* (Villers), for example, are known to live as long as 11 years. Fecundity as high as 2000 eggs per female has been recorded in some species (Hopkin and Read 1992).

Millipedes (Fig. 2.2) are detritivores, enrich soil system, acting as agents of decomposition by feeding on dead plant matter, such as leaf litter and wood, some also browsing on fungal mycelia and as accelerators in the nutrient release. Decomposition of the leaf litter by millipedes is by fragmentation and addition of microflora through fecal pellets (Kubiena 1955). The release of mineral nutrients into the soil is by feeding and defecation. Trace fossils attributable to burrowing by millipedes and including presumed fecal matter have been found in strata of late Ordovician (Richmondian) age, indicating that these animals have been active in soil processes for perhaps 445 million years (Retallack and Feakes 1987).

Among millipedes, the polydesmids digest woody plant residues. Millipedes belonging to the genus *Fontaria* are mull formers where as *Jonespeltis splendidus* is a humus-forming agent in the soil (Bano et al. 1976). Millipedes being largely responsible for mull production consume large quantities of litter and are instrumental in bringing down the carbon to nitrogen ratio from 30:1 to 10:1 (Blower 1956). With regard to ash mineralization, ash content increment is found in the excrements of the millipedes, *Glomeris marginata* and *Narceus annularis*. Increase in mineral content is also seen in the excrements of *Jonespeltis splendidus* (Bano and Krishnamoorthy 1977). Millipedes apart from being the litter feeders are also coprophagous. Coprophagy also leads to mineralization and improves carbon: nitrogen ratio in the soil. The feces of millipedes with high pH facilitate the growth and concentration of nitrogen-fixing bacteria.

Chilopoda

Centipedes are widely distributed in moist habitats throughout the tropical and temperate regions of the world. These are predominantly woodland species but are also common in grasslands and moorlands (Raw 1967). Centipedes are nocturnal and live in dark obscure place, under fallen logs, and in crevices in the soil. Since they cannot burrow into the soil, they utilize available crevices for shelter. Many species of centipedes are cave dwellers and a few of the geophilomorphs are marine.

Centipedes are generally predaceous (Fig. 2.2). The poisonous claws are used in securing their preys. Geophilids devour small soil-inhabiting arthropods and enchytraeid worms. *Lithobius variegatus* and *Lithobius* sp. feed on aphids, Collembola, mites, spiders, other centipedes, nematodes, and molluscus in addition to variable quantities of leaf litter. *Lithobius forficatus* in captivity readily accept flies, moths, and some noctuids. Scutigeromorphs are entirely insectivorous; scolopendromorps have a wide range of diet. *Scolopendra* are also known to feed on insect pests of various crops and slugs. Predatory associations of *Scutigera* sp. were found with termites, in the galleries of the fungus garden (Rajagopal and Veeresh 1981). So, to a certain extent, centipedes help in biological control of crop pests.

2.5.1.10 Isoptera (Termites)

Termites are more familiar insects in the tropics and subtropics (Fig. 2.1). They are eusocial, polymorphic insects and live in small to large colonies. 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. Their role in the decomposition of wood and other cellulose material is very important. Termites digest cellulose by virtue of their possessing intestinal bacteria and protozoa. Termites also form a source of food for many animals including human beings.

Isoptera order has over 2600 described species in 281 genera (Kambhampati and Eggleton 2000). These social insects do*m*inate soil arthropod assemblages across much of the dry tropics and in dry temperate regions. Termites attain their highest diversity in the tropics (Bignell and Eggleton 2000). Termites are known to inhabit soil and wood. The soil-inhabiting termites are quite common as mound builders above the ground or as subterranean nest builders. Wood-inhabiting termites are mostly arboreal and construct nests either inside or on the trees. Soil-inhabiting termites form a dominant group of soil fauna which are known to play an important role in the rapid turnover of organic matter in the ecosystem. The transportation and transformation of mineral and organic components of soils and plants are related to their numbers.

Food is collected by the workers; food consists of plant materials, either living or entirely decomposed. This food is obtained from cellulosic materials like wood, grasses, herbs, leaf and plant litter, dung, humus, fungi, etc. Food is provided to the members of the colony in two ways: (1) nymphs and reproductives, incapable of feeding themselves, are fed by the workers either by the stomodeal or proctodeal food. Stomodeal food, a clear liquid or regurgitated food, is the sole nourishment for functional reproductives and soldiers. (2) Proctodeal food is a liquid excretion from rectal pouches and in the lower termites, it includes protozoan fauna. Young ones of lower termites are fed by proctodeal food as the protozoa is essential for digestion of cellulose. Workers collect food both for their consumption and also for the other individuals in the colony, which consists of any plant material.

Decomposition by Termites

Wood-eating termites influence decomposition of woody litter, like branches, logs, tree stumps, etc. Occasionally the decomposition of dung of grazing animals, a significant source of organic matter, is strongly influenced by the soil fauna, notably various Coleoptera, and, in some cases, termites (Ferrar and Watson 1970).

N. exitiosus, in dry sclerophyll forest, consumes 16–17 % of total annual fall of woody litter, and in Nigeria, the rate of decay of wood is largely dependent on the activities of termites. In a tropical rain forest, many fungus-growing termites carry much soil and microorganisms into wood. They are dominant litter consumers in the forest. Because of this they are excellent agents to combine organic matter with microorganisms. Veeresh et al. (1982) found significant reduction in the available carbon and potash in plots where termites (*O. wallonensis*) were allowed to feed on dung, leaf litter, and soft wood compared to plots protected from termite attack.

2.5.1.11 Ants

Ants occupy unique position among all insects on account of their dominance in both the number of species in a single family Formicidae (7600 species) and the number of individuals under each species. Numerically each colony has several thousands of individuals. In a colony of *Myrmicaria brunnea* (Myrmicinae), the number varies from 3800 to 13,500 individuals. In case of *Tetramorium caespitum*, the number of individuals varies from 1395 to 30,943.

Ants are found everywhere from the arctic regions to the tropics, from the timber line on the loftiest mountains to the shifting sands of the dunes and sea shores, and from the dampest forest to the driest deserts (Wheeler 1910). Ants do not depend on any one type of food. They build perfect nests like termites or bees. More dominant species have learnt to maintain more number of queens in a colony rather than depend on only one queen (*Solenopsis*, *Monomorium*, and others have more than one queen).

As a group, ants are beneficial and many species deserve our protection. They are useful in the following ways:

1. *Hasten the decomposition of organic substances*: The observations of Forel (1910) reveal that an ant colony brings 28 dead insects per minute which account for 100,000/day during its active period. The same will be more in tropical countries.
2. *Act as predators of other harmful insects*: Four Italian species, namely, *Formica lugubris*, *F. aquilaria*, *F. rufa*, and *F. polyctena*, have been used to protect the alpine coniferous forests against damage by insects (Pavan 1962).
3. *Help in moving soil while excavating nests*: According to Branner (1910), ants are so abundant that they replace earthworms as the chief earth movers in the

tropics. Studies made by Lyford (1963) have shown that they are nearly as important as earthworms in cold temperate forests as well. Many young naturalists have employed them for skeletonizing small vertebrates. In Europe, cocoon of Fallow ant has been used as bird food. Many years ago formic acid was distilled from worker ants. In Mexico the garments affected by caterpillars were freed by placing them on large hills of *Formica* and *Pogonomyrmex. Pogonomyrmex occidentalis* was useful in bringing fossil mammals to the surface. Honey ants (*Myrmecocystus melliger*) were used by the Indians for food and medicinal purposes. The huge heads of the soldiers of the South American leaf-cutting ant (*Atta cephalotes*) have been employed by the native surgeons in closing wound. *Oecophylla* was a source of food for many Indians.

2.5.1.12 Other Soil Insects

Other soil insects like, Crickets, Mole crickets, Grasshopper and grubs of scarabid beetles and caterpillar of moths and butterflies etc., also play on important role in maintaining soil fertility, structure and texture, and in rendering the soil porous. The porosity of soil helps in water percolation and this helps in the growth and development of roots of plants. Insects also attract microorganisms like soil bacteria, fungi which in turn variously affect soil biota. Some of these soil borne bacteria and fungi take part in decomposition which adds to the organic matter content of the soil. The insects also help in upturning surface soil to subsurface and also contribute to nutrient status of the soil. Thus, other insects impact soil conditions at microhabitat level.

2.6 Functional Role of Arthropods in Maintaining Soil Fertility

The term “soil fertility” denotes the degree to which a soil is able to satisfy plant demands for nutrients (including water) and a physical matrix adequate for proper root development. Arthropods function on two of the three broad levels of organization of the soil food web. They are “litter transformers” or “ecosystem engineers.” Litter transformers, of which the micro arthropods comprise a large part, humidify ingested plant debris, improving its quality as a substrate for microbial decomposition and fostering the growth and dispersal of microbial populations. Ecosystem engineers are organisms that physically modify the habitat and regulate the availability of resources to other species (Jones et al. 1994). In the soil, this entails altering soil structure, mineral and organic matter composition, and hydrology. Ants and termites are the most important arthropod representatives of this guild, the latter group having received greater share of research attention (Lobry and Conacher 1990).

2.6.1 Influence of Arthropods on Nutrient Cycling

More than 90 % of net terrestrial primary production ultimately enters detritus food webs, where it is decomposed and recycled. Much of it originates in leaves and woody materials falling to the soil surface. Plant litter is a mixture of labile substrates (e.g., sugars, starch) easily digested by soil biota and other components (cellulose, lignins, tannins), more resistant to breakdown (Coleman et al. 2004). Decomposition of this material results from an interaction between physical and biological processes. Litter first must be physically weathered before it becomes suitable for further degradation by the soil microflora and fauna. Fungi are the important initial colonizers of plant litter (Harley 1971). With increasing disintegration and solubilization of the substrate, bacteria increase in importance. After this initial microbiological phase, the breakdown process slows and might come to a halt if not followed by animal activity. Saprophagous arthropods affect decomposition directly through feeding on litter and adhering microflora, thus converting the energy contained therein into production of biomass and respiration and, indirectly, through conversion of litter into feces and the reworking (reingestion) of fecal material, comminution of litter, mixing of litter with soil, and regulation of the microflora through feeding and the dissemination of microbial inoculum. Only a small proportion of net primary production is assimilated by soil arthropods (e.g., <10 % in oribatids, 4–20 % in millipedes and isopods). Thus, the indirect influence of these consumers on decomposition and soil fertility is of greater importance (Chew 1974). The influence of the soil fauna on decomposition processes is greatest in the humid tropics, where plant litter decomposition occurs most rapidly. This is due largely to the actions of the micro arthropods (Madge 1965).

2.6.1.1 Litter Feeding and Comminution

A major contribution of arthropods to the decomposition and humification processes is through the comminution of plant debris (Zimmer 2002). The physical fragmentation involved destroys the protective leaf cuticle, exposes cell contents, and increases water-holding capacity, aeration, and downward mobility of particulate and soluble substances. Comminution of plant litter is brought about largely by the feeding activity of saprophagous animals and, during passage through the digestive system, is accompanied by catabolic changes. The unassimilated residue from the commutative and catabolic processes is excreted as feces, typically smaller in size and of different chemical composition than the ingested food. The plant matter passing out in feces also presents an increased surface area to be attacked by microorganisms.

As much as 20 % of total annual litter input may be processed by the feeding activity of Collembola (Petersen 1994), a like proportion by that of oribatid mites, with about 3–10 % accounted for by Isopoda and Diplopoda and up to 60 % by termites (Collins 1981). Symphyla were estimated by Edwards (1973) to contribute about 2 % to annual litter turn over. Collins (1983) suggested that the biomass processed by termites commonly might be two or three times greater than the actual amount of litter consumed. Depending on the species involved, their densities, and the botanical composition, the mean litter comminution by millipedes in European forests ranged from 59 to 719 mg dry weight/ m^{-2}/ day^{-1}. Coprophagy is common in these arthropods and may be crucial to ensuring proper nutrition. In one study, the feces of millipedes showed an increase in pH, from 5.5 to 7.7, over that of the litter ingested and an eight fold increase in moisture content, providing a favorable substrate for increased microbial, particularly bacterial, activity. The bacterial biomass and digestion products improved the nutritional value of fecal pellets, which, on reingestion, provided a source of readily assimilable nutrients. Because of the large quantities of litter that they process, millipedes often are among the most important contributors of all soil invertebrates, to litter decomposition in moist, undisturbed habitats (Curry 1994). In habitats, in which earthworms are absent or rare, such as the acidic soils of coniferous forests, Collembola may assume a much greater role in physical breakdown of organic matter.

2.6.1.2 Mineralization of Nutrient Elements

Mineralization is the catabolic conversion of elements, primarily by decomposer organisms, from organic (i.e., bound in organic molecules) to inorganic form, such as the generation of CO_2 in the respiration of carbohydrates and breakdown of amino acids into ammonium (NH_4^+) and ultimately nitrate (NO_3). The direct or indirect actions of arthropods in processing plant litter increase available nutrient concentrations in the soil. Microorganisms efficiently convert the low-quality, recalcitrant resources of plant litter, such as the structural polymers comprising cell walls, into living tissue with much narrower carbon: nutrient ratios and of higher food value for animals, providing a rich source of nutrients at low metabolic cost to the consumer. A major proportion of the nutrients in the litter/soil system is concentrated and temporarily stored, or immobilized, in microbial biomass and subsequently in consumers, particularly the micro arthropods.

The microbial mineralization of nutrients may be stimulated by arthropod grazing. Several studies (Filser 2002) have demonstrated that grazing by Collembola has a strong stimulatory effect on fungal growth and respiration. Carbon mineralization by fungi and bacteria in comminuted litter was enhanced by an optimal level of grazing by micro- and macro arthropods; increased grazing pressure above the optimum inhibiting microbial respiration. Collembolan grazing on fungi can result in increased mobilization of available N and Ca, with implications for nutrient availability in particular environments, such as acidic forest soils, in which large nutrient pools tend to be immobilized in accumulated organic matter. Arthropod grazing on the microflora also acts to regulate the rate of decomposition, preventing sudden microbial blooms with the result that nutrients are mineralized and released from detritus, and made available for plant uptake, in a controlled and continuous fashion and their loss from the system minimized (Reichle 1977).

Arthropods influence the distribution of microbial populations in the soil by transporting microbes or their propagules on or in their bodies. For example, millipedes have large numbers of conidia of Streptomyces spp. adhering to their cuticle and dense populations of gut bacteria of the Actinomycetales, Bacillales, and Enterobacteriales, which were spread in feces. The microfloras have limited inherent capacities for movement and may remain for long periods in inactive resting stages if local conditions are unsuitable for growth and reproduction. Termites and their constructions function importantly in the replenishment of soil nutrients in natural ecosystems. The uniqueness of the involvement of termites in litter turnover and nutrient cycling was ably summed up by Lee and Wood (1961): "The combination of foraging for food over a wide radius from the nest and returning it to the nest…intense degradation of the plant tissue collected, and use of the excreted end products of digestion for mound-building resulting in their removal from participation in the plant/soil system for long periods, sets termites apart from other soil animals in their influence on soil organic matter." *Together with earthworms, termites are thought to contribute more to litter breakdown than all other soil-inhabiting invertebrates.*

Ant nests also may contain higher concentrations of nutrients than surrounding soil. Large amounts of organic matter from plant and animal (prey, carrion) sources accumulate in refuse dumps within nests. This material, combined with metabolic wastes and secretions from the ants themselves, may become incorporated into nest soil and undergoes decomposition and mineralization by the microflora, leading to an accumulation and local concentration of nutrients (Petal 1978). The organic matter content of soil worked by ants was reported to be 1.5 times greater than that of control soil. The increases in nutrient (e.g., cation) and organic matter content are likely factors influencing the generally observed shift in pH values toward neutral in ant-modified soil (Frouz and Jilková 2008). In infertile soils with low organic matter content and low rates of decomposition, predators, such as ants, speed the return to the soil of nutrients concentrated in the tissues of other animals (Petal 1978). This singular contribution of ants to organic matter turnover was recognized and emphasized more than a century ago by Wheeler (1910). A similar process results from the activities of those groups indirectly herbivorous in diet. The leaf-cutting attine ants (Myrmicinae: Attini), for example, are considered the chief agents for introducing organic matter, in the form of discarded fungus gardens, into the nutrient-poor soils of the New World tropics; this material then becoming available to other organisms for further decomposition. The activities of this tribe of ants clearly facilitate the decomposition of plant materials and promote nutrient cycling. Farji-Brener and Tadey (2009) concluded that the magnitude of the contribution of leaf-cutter ants to soil fertility was among the highest of any animal group.

2.6.2 Influence of Arthropods on Soil Structure

Biology plays a major role in the stabilization of soil structure (Oades 1993). Among the more biologically significant attributes of soil are the spatial organization of soil particles and of the pore spaces and voids among them, the combination of the particles into aggregates, and the stability of the aggregates in water. A favorable soil structure ensures adequate nutrient retention, aeration, and water-holding capacity below ground, facilitates root penetration, and prevents surface crusting and erosion of topsoil. Arthropods affect the structural properties of soils in various ways.

2.6.2.1 Soil Mixing and the Development of Pores and Voids

Biotic pedoturbation refers to the displacement or mixing of soil material through the actions of organisms (Wilkinson et al. 2009). In general, the mesofauna are not considered important in this process because they are too small to move most soil particles (although Collembola and oribatid mites are said to make active "micro-tunnels" in the soil matrix (Rusek 1985); these animals instead rely on existing cracks and crevices and the channels and spaces created by the larger fauna to aid their mobility within the soil (Oades 1993). The subterranean network of tunnels and galleries that comprise termite and ant nests plays an important role in enhancing aeration and water infiltration through the soil profile, increasing water storage, and retention of top soil. Termites have been reported to work the soil to depths of 50 m or more (Lepage et al. 1974). In experimental studies, Elkins et al. (1986) and Whitford (1991) found plots, from which subterranean termites had been eliminated, to have significantly reduced water infiltration and storage and increased run-off and sediment flow (bed load) compared to plots populated with termites. Mando et al. (1996), Mando and Miedema (1997), and Mando (1997) showed that active encouragement of termite activity through the application of surface mulches significantly improved the hydraulic properties of degraded soils. Under such conditions, soil, in which termites (*Macrotermes subhyalinus* [Rambur] and *Odontotermes* sp.) were active, had infiltration rates ranging from 2 to 6 to above 9 $cm^3 s^{-1}$, two to three times those in soil without termites (Léonard and Rajot 2001).

The infiltration pathways and sinks provided by ant nests limited post fire hillslope erosion by reducing overland water flow rates following heavy rainfall events (Richards 2009). Experimental crop yield increased 36 % and infiltration rates threefold in plots supporting ant and termite populations over those in plots, from which the insects had been, excluded (Evans et al. 2011). The system of chambers and galleries comprising ant and termite nests, increases the porosity of soil, improving aeration and water infiltration, together with the organic matter (from feces, salivary, and other secretions). Further food remnants accumulating therein, enhances water-holding capacity and creates an environment favorable for the penetration of plant roots (Petal 1978) between closely packed soil particles and excavated burrows (Hopkin and Read 1992).

Jacot (1940) identified millipedes as one of the groups instrumental in mixing organic matter with the mineral soil. Oribatids also are thought to contribute to the deep mixing of organic material by their movements to, and deposition of feces in, lower layers of the soil (Wallwork 1970). Similarly, the tendency for symphyla to move rapidly up and down the soil profile serves to distribute their feces widely throughout the soil. Fecal materials are major constituents contributing to the formation of stable soil aggregates (see discussion below), which are important in maintaining adequate water infiltration and drainage (Tisdall and Oades 1982). The activities of ants and termites below ground may have a significant influence on the particle size distribution within the soil. In particular, the selective removal of the finer and smaller soil particles from lower in the profile may result in a greater contrast in texture between the topsoil and subsoil horizons, with implications for abiotic pedogenic processes through the soil profile, because they are more widespread than earthworms; ants, in the aggregate, had a much greater influence on soils. This view largely has been supported by a sizeable body of research over the ensuing years (Paton et al. 1995), which indicates global rates of ant-mediated pedoturbation of *ca*. 10 tonnes/ ha^{-1}/ $year^{-1}$. Lyford (1963) estimated that at least 60 g m^{-2} of soil in a New England (USA) forest was transferred annually by ants from the B horizon to the surface in the process of mound building and suggested that the entire A horizon (25–46 cm thick) of some of the virgin brown podzolic soils of the region was the product of such pedoturbation over a period of 3000–4000 years. An estimated 6 m^3 (7.4 tonnes dry weight) of soil ha^{-1} was moved by ants (*Formica cinerea* Mayr) from the B horizon to the surface to form the upper parts of extant mounds in a North American prairie. Bulk density (a function of porosity and organic matter content) of the deposited material was significantly lower than that of the surrounding soil (~0.29–0.53 vs. 1.04 g cm^{-3}). Nest building by *Atta cephalotes* (L.) in a tropical forest resulted in displacement to the surface of an estimated 460 tonnes of subsoil/ ha^{-1} over the average colony's life span. The authors concluded that leaf-cutter ants played a major role in soil genesis and development in New World tropics.

Termite mounds often are abundant in tropical regions, numbering in excess of 1000 /ha^{-1} and representing, in aggregate, many tonnes of soil (Lee and Wood 1961). In regions, in which mounds are numerous, an estimated 1 tonne or more / ha^{-1} of mineral soil from the lower horizons was deposited on the surface annually. The estimated amount of soil brought to the surface by subterranean termites in a temperate desert was somewhat lower, at about 750 kg /ha^{-1} /$year^{-1}$, and included a rich clay component (Nutting et al. 1987). The nest-building activity of termites was calculated to result in pedoturbation of a 20–37-cm-thick layer of soil in 1000 years, contributing significantly to soil turnover. Role of arthropods in structuring the soils is shown in Fig. 2.4.

2.6.2.2 Formation of Soil Aggregates

Soil aggregates, or peds, the basic units of soil structure, are formed by natural processes, commonly involving the activity of organisms (Hole 1981; Lynch and Bragg 1985). Fecal pellets, combining fine mineral particles with undigested organic matter, are the major contribution of invertebrates to the formation of soil aggregates (Rusek 1985; Pawluk 1987). Mucilaginous substances, by-products of microbial decomposition, bind the feces with other soil components into stable microstructures (Oades 1993; Harris et al. 1966). These organomineral complexes are substrates, on which inorganic nutrients may become adsorbed and so available to plants (Kunhelt 1976). The resulting humus, an amorphous colloidal material comprising partially decomposed organic matter that makes up topsoil and increases the soil's capacity to store nutrients (example, cations) and prevent their rapid leaching, thus is largely derived from animal feces (Ciarkowska and Niemyska-Łukaszuk 2002; Loranger et al. 2003). The humus of well-developed soils represents a significant pool of macronutrients, such as N, P, K, Ca, and Mg, which may be stored in amounts exceeding 1 tonne/ ha^{-1}. It also is involved in chelation reactions, which aid in the micronutrient nutrition of plants, buffers the soil against rapid changes in

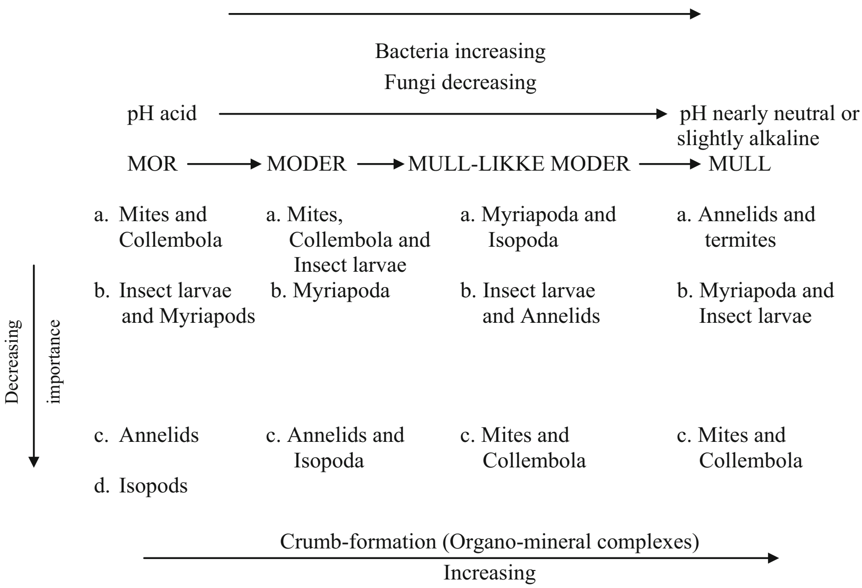

Fig. 2.4 Soil categories, pH, and biota responsible for soil structure (Wallwork 1970)

pH, and supports an abundance and diversity of microorganisms, promoting increased mineralization activity.

Organomineral microaggregate structures from the feces of soil-feeding termites also are thought to aid in increasing structural stability and porosity of tropical soils. In areas of high termite activity, these micropeds may comprise 20 % of the soil matrix (Kooyman and Onck 1987). Arthropod feces generally play a larger role in the formation of the moder and mor types of humus and in the formation of primitive soils. However, although earthworms generally are considered to dominate in mull-type soils (Bardgett et al. 2005), arthropods, such as millipedes, also may contribute substantially to these or to mull-like formations (Romell 1935). By contrast, a lack of millipedes, as well as earthworms, in the mor soils of coniferous forests is one of the main reason for the slow decomposition of pine needles (Hopkin and Read 1992). The volume of feces contributed may be considerable. For example, collembolan populations, at densities typical of forest soils, were estimated to produce around 175 cc of fecal pellets/ m^{-2} annually, equivalent to the formation of a soil layer of roughly 0.2 mm in depth. The production of fecal pellets by desert isopods (*Hemilepistus reaumuri*) ranged from 2 to 41 g/ m^{-2} /$year^{-1}$, depending on site conditions (primarily moisture regime), subsequently to be redistributed and mixed with soil during rainfall events (Yair and Rutin 1981). Striganova (1975) estimated annual millipede consumption of litter in woodland that results in a layer of fecal pellets 0.5–1 cm thick soil surface. On rocky sites, millipedes (Glomeridae) may facilitate the process of succession by consuming detritus accumulating in cracks and depositing excrement there, providing a substrate favorable for the

Table 2.1 List of minor soil insects and their role

Name and family	Feeding habit	Habitat preferred	Functional roles
Cricket, Gryllidae	On living/dry, dead organic matter	Dry hot niches, live in burrows/under logs	Pests of crops, upturn soil
Mole cricket, Gryllotalpidae	Carnivorous, crops	Soil dwelling, dig soil	Pests of crops, upturn soil
Grasshoppers, Acrididae	Phytophagous	Soil dwelling, dig soil	Pests of crops
Ground beetles, Carabidae	Carnivorous, crops	Under stones, rotting wood/under bark	Pests of crops, upturn soil
Tiger beetles, Cicindelidae	Carnivorous	Soil	Upturn soil
Rove beetles, Staphylinidae	Carnivorous, crop	Bark/decaying wood	Decompose decaying matter
Wasps, Vespidae	Carnivorous	Soil	Upturn soil

colonization of higher plants (Kunhelt 1976). The relative abundance of hemi- and edaphic arthropods in different soils is presented in Tables 2.1 and 2.2.

2.6.3 Current Threats to Soil Biodiversity

A majority of human activities result in soil degradation, impacting the services provided by soil biodiversity elements. Soil organic matter depletion and soil erosion are influenced by inappropriate agricultural practices, overgrazing, vegetation clearing, and forest fires. It has been observed, for example, that land without vegetation can be eroded more than 120 times faster than land covered by vegetation, thus lose less than 0.1 tonne of soil per ha/year. The activity and diversity of soil organisms are directly affected by the reduction of soil organic matter and indirectly by the reduction in plant diversity and productivity (Bengtsson et al. 2005). Land use management practices affect biodiversity. Within rural lands, soil biodiversity tends to decrease with the increasing intensification of farming practices (e.g., use of pesticides, fertilizers, heavy machinery) (Haygarth and Ritz 2009; Joris et al. 2013). Climate change may be the second most important factor affecting soil biodiversity. Climate change is likely to have significant impacts on services provided by soil biodiversity elements (Schils et al. 2008).

The pollution of soils is mostly a result of industrial activities and use of fertilizers and pesticides. Toxic pollutants can destabilize the population dynamics of soil organisms by affecting reproduction, growth, and survival (Gardi and Jeffrey 2009). Genetically modified crops (GMOs) may also be considered as a growing source of pollution for soil organisms. Most effects of GMOs are observed on chemical engineers, by altering the structure of bacterial communities, bacterial genetic transfer, and the efficiency of microbial-mediated processes. GMOs have also been shown to have effects on earthworm physiology, but to date little impacts on biological regulators are known (Daane et al. 1996).

Table 2.2 Approximate abundance (number m^{-2}) of hemi- and edaphic arthropods in different soils

Soil type							
Body-size group	Taxon	Tundra (arctic alpine)	Mor (boreal forest)	Mull (warm temperate forest)	Temperate grassland (prairie)	Tropical savanna	Tropical forest
Mesofauna	Microarthropoda	100,000	40,000	40,000	25,000	2000	15,000
	Symphyla	0	3000	600	1000	2000	800
Macrofauna	Diplopoda/Isopoda	0	500	1000	500	<1	400
	Formicidae	0	50	3000	1000	2000	800
	Isoptera	0	0	1000	1000	4000	5000

Due to globalization, invasives have become an important threat to soil biodiversity. Exotic species are called invasive when they become disproportionally abundant. Invasive species can have major direct and indirect impacts on soil services and native biodiversity. Invasive plants will alter nutrient dynamics and thus the abundance of microbial species in soil, especially of those exhibiting specific dependencies (e.g., mycorrhiza). Biological regulator populations tend to be reduced by invasive species, especially when they have species-specific relationships with plants. Soil biodiversity can serve as a reservoir of natural enemies against invasive plants. Setting up such biological control programs could save billions of rupees in prevention and management of invasive species (Seifert et al. 2009).

Soils are integral parts of ecosystems and are maintained in a fertile state largely through the actions of their constituent biota. Fertility is a function of a soil's capacity to provide plants not only with essential nutrients for growth and reproduction but also with a physical matrix that facilitates root growth and respiration and maintains its structural integrity against erosive forces. Arthropods influence soil fertility in two principal ways. First, they promote the decomposition of plant litter directly and indirectly, by transforming it physically and chemically into substrates amenable to further degradation. The higher assimilation efficiencies of termites allow these animals to convert a greater proportion of ingested litter directly into biomass that is possible for other soil arthropods, whereas the main contribution of the Collembola, Oribatida, Myriapoda, and Isopoda to nutrient cycling is via the indirect route, as secondary decomposers, conditioning litter, through comminution and passage through the gut, for further breakdown by the microflora. The nests of termites and ants, with their incorporated fecal materials, waste dumps, or fungal gardens, also provide rich substrates for the microbial degradation and mineralization of organic matter. The end result of these processes is the conversion of complex organic molecules into simpler, inorganic forms that can be used by plants. Arthropod grazing on microbial populations also may serve to regulate the availability of nutrients to plants, ensuring their release in a controlled and continuous manner and minimizing their loss from the root zone.

The second major way, in which arthropods contribute to the maintenance of soil fertility, is through their effects on the physical structure of the soil. Ants and termites are the pre eminent earth movers in many regions of the world and may surpass earthworms in this capacity in some cases. The pedoturbation resulting from their activities brings substantial amounts of subsoil to the surface, increasing the mineral content of the topsoil and providing sites for ion exchange in the root zone. The tunneling and burrowing of arthropods provide channels for air passage and water infiltration and also serve to mix organic matter into the upper soil layers. The feces of arthropods serve as nuclei for the accretion of soil aggregates and basic units of a soil's structure. This is important in maintaining integrity and are a significant factor in the formation of humus, which contributes to water and nutrient retention in the soil. A select list of endangered soil arthropods is provided (Table 2.3).

Table 2.3 A select list of endangered soil arthropods in South Asia

Class	Common name	Scientific name	Country	Reasons
Arachnida	Peacock tarantula	*Poecilotheria metallica*	India	Habitat quality is decreasing
Crustacea		*Perbrinckia punctata*	Sri Lanka	Habitat degradation
	Singapore freshwater crab	*Johora singaporensis*	–	Habitat development and degradation
Diplopoda	Major black millipede	*Doratogonus major*	South Africa	Habitat destruction
Insecta	Delta green ground beetle	*Elaphrus viridis*	California, USA	Invasive plants
	Cromwell chafer	*Prodontria lewisi*	New Zealand	Habitat degradation and predation by introduced species
	Dracula ant	*Adetomyrma venatrix*		Habitat loss
	Frigate Island giant tenebrionid beetle	*Polposipus herculeanus*	Frégate Island	Fungal diseases

Source: endangered species 2010: arthropods part 1 – Arachnids, Crustaceans and millipedes, part II insects by Thonoir

2.7 Conservation Priorities

Almost 98 % of earth's diversity is in terrestrial ecosystem, of which soil is the main component, so conservation of soil and its components like arthropods is critically important. Planting of trees on the easily eroded, easily compacted, and readily oxidized soils of the tropics is urgently required. Research in the temperate lands has shown that sowing of wildflower seed mixtures can be highly beneficial to insects (Samway 1994) and other arthropods. In the tropics regulating the human populations, plant refugia with indigenous species, restoration of wetlands/water bodies, judicious use of pesticides and chemicals, and preventing overexploitation of natural resources will go a long way in restoration of habitats. Restricting extensive landscape modifications and minimizing development and destruction of fertile soils is key to the arthropod conservation. Some of the endangered soil arthropods can be saved by captive breeding. Sustainable use of resources should form basis for soil restoration ecology. The best step would be to preserve as many landscapes as possible in natural state. Arthropods because of their small size, not appealing shapes, are generally not considered valuable for conservation. The knowledge of these creatures is lacking in the public. The landscapes which soil arthropods inhabit should be preserved or sustainably used, as they play a major role in the ecosystem.

References

Bagyaraj DJ (2011) Microbial biotechnology for sustainable agriculture, horticulture and forestry. NIPA Publishers, New Delhi

Bagyaraj DJ (2014) Interaction between arbuscular mycorrhizal fungi and the soil organisms and their role in sustainable agriculture. In: Singh DP, Singh HB (eds) Trends in soil microbial ecology. Studium Press LLC, Houston, pp 257–280

Bano K, Krishnamoorthy RV (1977) Changes in the composition of soils due to defecation by the millipede *Jonespeltis splendidus* (Verhoeff). Mysore J Agric Sci 11:561–566

Bano K, Bagyaraj DJ, Krishnamoorthy RV (1976) Feeding activity of millipede *Jonespeltis splendidus* Verhoeff and soil humification. Proc Indian Acad Sci 82:1–11

Bardgett RD, Usher MB, Hopkins DW (2005) Biological diversity and function in soils. Cambridge Univ Press, Cambridge, pp 172–188

Barrios E (2007) Soil biota ecosystem services and land productivity. Ecol Econ 64:269–285

Barron GL (1977) Topics in mycology No.1 The nematode destroying fungi. Canadian Biological Publications Ltd., Guelph, p 140

Bengtsson J, Ahnstrom J, Weibull AC (2005) The effects of organic agriculture on biodiversity and abundance: a meta-analysis. J Appl Ecol 42:261–269

Bignell DE, Eggleton P (2000) Termites in ecosystems. In: Abe T, Bignell DE, Higashi M (eds) Termites: evolution, sociality, symbioses, ecology. Kluwer Academic Publishers, Dordrecht, pp 363–387

Blower G (1951) A comparative study of the chilopod and diplopod cuticle. J Microsc Sci 92:141–161

Blower JG (1956) Some relations between millipedes and the soil. In Proceedings of 6th Congres International de la Science du Sol, Paris III, pp. 169–176

Boellstorff DL (2008) Estimated soil organic carbon change due to agricultural land management modifications in a semiarid cereal-growing region in Central Spain. J Arid Environ 73(3):389–392

Boudreaux HB (1979) Arthropod phylogeny with special reference to insects. Wiley, New York, p 320

Branner JC (1910) Geologic work of ants in tropical America. Bull Geol Soc Am 21:449–496

Brauman KA, Daily GC, Duarte TK, Mooney HA (2007) The nature and value of ecosystem services: an overview highlighting hydrologic services. Annu Rev Environ Resour 32:67–89

Brussaard L, de Ruiter PC, Brown GG (2007) Soil biodiversity for agricultural sustainability. Agric Ecosys Environ 121(3):233–244

Chapman AD (2009) Numbers of living species in Australia and the world, 2nd edn. Australian Government, Department of the Environment, Water, Heritage and the Arts, Canberra, p 80

Chew RM (1974) Consumers as regulators of ecosystems: an alternative to energetics. Ohio J Sci 74:359–370

Christiansen K (1964) Bionomics of collembola. Annu Rev Entomol 9:147–148

Ciarkowska K, Niemyska-Łukaszuk J (2002) Microstructure of humus horizons of gypsic soils from the Niecka Nidziańska area (South Poland). Geoderma 106:319–329

Coleman DC, Crossley DA Jr, Hendrix PF (2004) Fundamentals of soil ecology, 2nd edn. Elsevier Academic Press, Burlington, p 386

Collins NM (1981) The role of termites in the decomposition of wood and leaf litter in the Southern Guinea savanna of Nigeria. Oecologia 51:389–399

Collins NM (1983) Termite populations and their role in litter removal in Malaysian rain forests. In: Sutton SL, Whitmore TC, Chadwick AC (eds) Tropical rain forest: ecology and management. Blackwell Scientific Publications, Oxford, pp 311–325

Constanza R, d'Arge R, Groot R, Farbe S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neil RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

Culliney TW (2013) Role of arthropods in maintaining soil fertility. Agriculture 3:629–659

Curry JP (1994) Grassland invertebrates: ecology, influence on soil fertility and effects on plant growth. Chapman & Hall, London, p 437
Daane LL, Molina JAE, Borry EG, Sadowsky MJ (1996) Influence of earthworm activity on gene transfer from *Pseudomonas fluorescens* to indigenous soil bacteria. Appl Environ Microbiol 62:515–521
Darwin C (1881) The formation of vegetable mould through the action of worms, with observations of their habits. Murry, London, p 326
Dash MC, Patra UC (1979) Worm cast production and nitrogen contribution to soil by a tropical earthworm population from a grass land site from Orissa India. Rev Ecol Biol Sol 16:79–83
Decaens T, Jimenez JJ, Gioia C, Measey GJ, Lavelle P (2006) The values of soil animals for conservation biology. Eur J Soil Biol 42:S23–S38
Dindal DL (1970) Feeding behavior of a terrestrial turbellarian *Bipalium adventitium*. Am Midl Nat 83:635–637
Edwards CA (1973) Biological aspects of the degradation and behavior of pesticides in soil. In Proceedings of 7th British insecticides and fungicide conference. pp. 811–823
Edwards CA (1990) Symphyla. In: Dindal DL (ed) Soil biology guide. Wiley, New York, pp 891–910
Edwards CA, Lofty JR (1972) Biology of earthworms. Chapman and Hall Ltd, London, p 283
Eisenbeis G, Wichard W (1987) Atlas on the biology of soil arthropods. Springer-Verlag, Berlin, p 437
Elkins NZ, Sabol GV, Ward TJ, Whitford WG (1986) The influence of subterranean termites on the hydrological characteristics of a Chihuahuan desert ecosystem. Oecologia 68:521–528
Evans TA, Dawes TZ, Ward PR, Lo N (2011) Ants and termites increase crop yield in a dry climate. Nat Commun 2, doi:10.1038/ncomms1257
Farji-Brener AG, Tadey M (2009) Contributions of leaf-cutting ants to soil fertility: causes and consequences. In: Lucero DP, Boggs JE (eds) Soil fertility. Nova Science Publishers, New York, pp 81–91
Ferrar P, Watson JAL (1970) Termites associated with dung in Australia. J Aust Entomol Soc 9:100–102
Filser J (2002) The role of collembola in carbon and nitrogen cycling in soil. Pedobiologia 46:234–245
Finlay R (2006) Identification of single species and communities. In: Luster J, Finlay R (eds) Handbook of methods used in Rhizosphere research. Swiss Federal Research Institute, Birmensdorf, pp 338–339
Forel A (1910) Glanures myrmecologianes. Ann Soc Entomol Belg 54:6–31
Frouz J, Jilková V (2008) The effect of ants on soil properties and processes (Hymenoptera: Formicidae). Myrmecol News 11:191–199
Gardi C, Jeffrey S (2009) Soil biodiversity. Joint Research Center, European Commission, Luxembourg, p 27
Gates GE (1961) Ecology of some earthworms with special reference to seasonal activity. Am Midl Nat 66:61–86
Ghaisas PS, Ranade DP (1981) Record of *Japyx solifugus* (Diplura) from Poona, UAS tech series – India, pp. 147–152
Giribet G, Edgecombe GD (2012) Reevaluating the arthropod tree of life. Annu Rev Entomol 57:167–186
Harley JL (1971) Fungi in ecosystems. J Appl Ecol 8(3):627–642
Harris RF, Chesters G, Allen ON (1966) Dynamics of soil aggregation. Adv Agron 18:107–169
Haygarth P, Ritz K (2009) The future of soils and land use in the UK: soil systems for the provision of land-based ecosystem services. Land Use Policy 26:S187–S197
Hole FD (1981) Effects of animals on soil. Geoderma 25:75–112
Hopkin SP (1997) Biology of the springtails (Insecta: collembola). Oxford University Press, Oxford, p 330
Hopkin SP, Read HJ (1992) The biology of millipedes. Oxford University Press, Oxford, p 233

Jacot AP (1940) The fauna of the soil. Q Rev Biol 15:28–58

Jegen G (1920) DieBedeutng der Encytraeiden fiir die Humus bildung. Landwirtsch Fb Schweiz 34:55–71

Jenny H (1980) The soil resource: origin and behavior. Springer-Verlag, New York, p 377

Jones CG, Lawton JH, Shachak M (1994) Organisms as ecosystem engineers. Oikos 69:373–386

Joris H, Caires E, Bini A, Scharr D, Haliski A (2013) Effects of soil acidity and water stress on corn and soybean performance under a no-till system. Plant and Soil 265:409–424

Kale RD, Krishnamoorthy RV (1979) Pesticidal effects of Sevin. R. (1-naphthyl-n-methyl carbamate) on the survivability and abundance of earthworm *Pontoscolex corethrurus*. Proc Indian Acad Sci 88B:391–396

Kale RD, Krishnamoorthy RV (1980) The calcium content of the body tissues and castings of the earthworm *Pontoscolex corethrurus* (Annelida: Oligochaeta). Pedobiologia 20:309–315

Kale RD, Krishnamoorthy RV (1981) Litter preference in the earthworm, *Lampito mauritii*. Proc Ind Acad Sci 90:123–128

Kambhampati S, Eggleton P (2000) Taxonomy and phylogeny of termites. In: Abe T, Bignell DE, Higashi M (eds) Termites: evolution, sociality, symbioses, ecology. Kluwer Academic Publishers, Dordrecht, pp 1–23

Kooyman C, Onck RFM (1987) The interactions between termite activity, agricultural practices and soil characteristics in Kisii District, Kenya. In Agricultural University Wageningen Papers 87-3, Agricultural University Wageningen: Wageningen, the Netherlands. pp. 1–120

Kubiena WL (1955) Animal activity in soil as a decisive factor in establishment of humus forms. In: McE Kevan DK (ed) Soil zoology, vol 2. Butterworths, London, pp 73–82

Kunhelt W (1976) Soil biology: with reference to the animal kingdom. Faber and Faber, London, p 483

Lee KE, Wood TG (1961) Termites and soils. Academic, New York, p 251

Léonard J, Rajot JL (2001) Influence of termites on runoff and infiltration: quantification and analysis. Geoderma 104:17–40

Lepage M, Morel G, Resplendino C (1974) Découverte de galeries de termites atteignant la nappe phréatique profonde dans le Nord du Sénégal. C R Acad Sci Sér D 278:1855–1858

Lobry de Bruyn LA, Conacher AJ (1990) The role of termites and ants in soil modification: a review. Aust J Soil Res 28:55–93

Loranger G, Ponge JF, Lavelle P (2003) Humus forms in two secondary semi-evergreen tropical forests. Eur J Soil Sci 54:17–24

Luster J, Göttlein A, Nowack B, Sarret G (2009) Sampling, defining, characterizing and modelling the rhizosphere – the soil science tool box. Plant and Soil 321:457–482

Lyford WH (1963) Importance of ants to brown podzolic soil genesis in New England. Harvard Forest Paper, Petersham

Lynch JM, Bragg E (1985) Microorganisms and soil aggregate stability. Adv Soil Sci 2:133–171

Madge DS (1965) Leaf fall and litter disappearance in a tropical forest. Pedobiologia 5:273–288

Maggenti AR (1981) Nematodes: development as plant parasites. Annu Rev Microbiol 35:135–154

Mando A (1997) The impact of termites and mulch on the water balance of crusted Sahelian soil. Soil Technol 11:121–138

Mando A, Miedema R (1997) Termite-induced change in soil structure after mulching degraded (crusted) soil in the Sahel. Appl Soil Ecol 6:241–249

Mando A, Stroosnijder L, Brussaard L (1996) Effects of termites on infiltration into crusted soil. Geoderma 74:107–113

Narayana Swamy BC, Nanjegowda D (1980) The Tardigrade *Macrobiotus* Sp. predaceous on plant parasitic Nematodes. Soil Biol Ecol News lett 1:9

Nielsen CO, Christensen B (1959) The enchytracidae, critical revision and taxonomy of European species. Natur Jutlandica 8–9:1–160

Norton DC (1978) Ecology of plant-parasitic nematode. Wiley, New York, p 268

Norton RA (1994) Evolutionary aspects of oribatid mite life histories and consequences for the origin of the astigmata. In: Houck MA (ed) Mites: ecological and evolutionary analyses of life-history patterns. Chapman & Hall, New York, pp 99–135

Norton RA, Behan-Pelletier VM (2009) Suborder oribatida. In: Krantz GW, Walter DE (eds) A manual of acarology. Texas Tech University Press, Lubbock, pp 430–564
Nutting WL, Haverty MI, LaFage (1987) Physical and chemical alteration of soil by two subterranean termite species in Sonoran desert grassland. J Arid Environ 12:233–239
Oades JM (1993) The role of biology in the formation, stabilization and degradation of soil structure. Geoderma 56:377–400
Overgaard Nielsen C, Christensen B (1959) The enchytraeidae – critical revision and taxonomy of European species. Naturhistorisk Museum, Aarhus
Patel HK, Patel RM (1959) Preliminary observations on the control of earthworms by soapnut (*Sapindus laurifolius* Vaw) extract. Indian J Entomol 21:251–255
Paton TR, Humphreys GS, Mitchell PB (1995) Soils: a new global view. Yale University Press, London, p 213
Pavan M (1962) La defence biologique des forest en italic avecless fourmis du groupe *Formica rufa* Symp. Genetica et biologica italic. Atti IV Congresso UIEIS Pavia 11:1–25
Pawluk S (1987) Faunal micromorphological features in moder humus of some western Canadian soils. Geoderma 40:3–16
Petal J (1978) The role of ants in ecosystems. In: Brian MV (ed) Production ecology of ants and termites. Cambridge University Press, Cambridge, UK, pp 293–325
Petersen H (1994) A review of collembolan ecology in ecosystem context. Acta Zool Fenn 195:111–118
Petersen H, Luxton M (1982) A comparative analysis of soil fauna populations and their role in decomposition processes. Oikos 39:288–388
Pimentel D (1997) Techniques for reducing pesticides: environmental and economic benefits. Wiley, Chichester
Powlson DS, Bhogal A, Chambers BJ, Coleman K, Macdonald AJ, Goulding KWT, Whitmore AP (2012) The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: a case study. Agric Ecosyst Environ 146:23–33
Prabhoo NR (1972) South Indian protura. Rev Ecol Biol Sol 9:711–718
Rajagopal D, Veeresh GK (1981) Thermophiles and teritariophiles of *Odontotermes wallonensis* (Isoptera : Termitidae) in Karnataka, India. Colemania 1(2):129–130
Raw F (1967) Arthropods (except Acari and collembola). In: Burges A, Raw F (eds) Soil biology. Academic, London, pp 323–362
Reichle DE (1977) The role of soil invertebrates in nutrient cycling. In: Lohm U, Persson T (eds) Soil organisms as components of ecosystems. Swedish Natural Science Research Council, Stockholm, pp 145–156
Retallack GJ, Feakes CR (1987) Trace fossil evidence for late Ordovician animals on land. Science 235:61–63
Richards PJ (2009) *Aphaenogaster* ants as bioturbators: impacts on soil and slope processes. Earth Sci Rev 96:92–106
Romell LG (1935) An example of myriapods as mull formers. Ecology 16(1):67–71
Rusek J (1985) Die bodenbildende Funktion von Collembolen und Acarina. Pedobiologia 15:299–308
Samway MJ (1994) Insect conservation biology. Chapman and Hall, London, p 358
Sayre RM (1971) Biotic influence in soil environment. In: Zukerman BM, Mai WF, Rhode RA (eds) Plant parasitic nematodes, vol I. Academic, New York, pp 235–256
Schils R, Kuikman P, Liski J, van Oijen M, Smith P, Webb J, Alm J, Somogyi Z, van den Akker J, Billett M, Emmett B, Evans C, Lindner M, Palosuo T, Bellamy P, Alm J, Jandl R, Hiederer R (2008) Review of existing information on the interrelations between soil and climate change. Altera, Wageningen, p 205
Schmalfuss H (2003) World catalog of terrestrial isopods (Isopoda: Oniscidea). Stuttg Beitr Naturkunde Ser A (Biol) 654:1–341
Seifert EK, Bever JD, Maron JL (2009) Evidence for the evolution of reduced mycorrhizal dependence during plant invasion. Ecology 90(4):1055–1062

Senapati BK, Dash MC, Rana AK, Panda BK (1980) Observation on the effect of earthworm in the decomposition process in soil under laboratory conditions. Comput Physiol Ecol 5:140–142

Sierwald P, Bond JE (2007) Current status of the myriapod class Diplopoda (millipedes): taxonomic diversity and phylogeny. Annu Rev Entomol 52:401–420

Stirling GR, Mankau R (1978) *Dactylella oviparasitica*, a new fungal parasite of *Meloidogyne* eggs. Mycologia 70:771–783

Stork NE, Eggleton P (1992) Invertebrates as determinants and indicators of soil quality. Am J Altern Agric 7:38–47

Striganova BR (1975) Dispersion patterns of diplopods and their activity in the litter decomposition in the Carpathian foothills. In: Vaněk J (ed) Progress in soil zoology. Academia, Prague, pp 167–173

Sutton S (1980) Woodlice. Pergamon Press, Oxford, p 144

Szucsich N, Scheller U (2011) Symphyla. In: Minelli A (ed) Treatise on zoology—anatomy, taxonomy, biology: the myriapoda, vol 1. Koninklijke Brill NV, Leiden, pp 445–466

Tembe VB, Dubash PJ (1961) The earthworms: a review. J Bombay Nat Hist Soc 58:171–201

Timonin MI (1961) The interaction of plant pathogen and *Scaptocoris talpa* Champ. Can J Bot 39:695–703

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. J Soil Sci 33:141–163

Turbé A, De Toni A, Benito P, Lavelle P, Ruiz N, Van der Putten WH, Labouze E, Mudgal S (2010) Soil biodiversity: functions, threats and tools for policy makers. Bio Intelligence Service, IRD and NIOO Report for European Commission (DG Environment), pp. 251

Veeresh GK, Rajgopal D, Mallik B (1982) Termites and fertility status of soil. VII International Colloquium of soil Zoology, 30th Aug–2nd Sept Louvain-La-Neuve, Belgium

Wallwork JA (1970) Ecology of soil animals. McGraw Hill, London, p 283

Wallwork JA (1982) Desert soil fauna. Prarger Publishers, New York, p 296

Wallwork JA (1983) Oribatids in forest ecosystems. Annu Rev Entomol 28:109–130

Wheeler WM (1910) Ants: their structure, development and behavior. Columbia University Press, New York, p 663

Whitford WG (1991) Subterranean termites and long-term productivity of desert rangelands. Sociobiology 19:235–243

Whitford WG, Freckman DW, Parker LW, Schaefer D, Santos PF, Steinberger Y (1983) The contributions of soil fauna to nutrient cycles in desert systems. In: Lebrun P, André HM, de Medts A, Grégoire-Wibo C, Wauthy G (eds) New trends in soil biology. Imprimerie J Dieu-Brichart: Ottignies-Louvain-la-Neuve, Belgium, pp 49–59

Wilkinson MT, Richards PJ, Humphrey GS (2009) Breaking ground, pedological geological and ecological implications of soil bioturbation. Earth Sci Rev 97:257–272

Winoto Suatmadji R (1969) Studies on effect of Tagetes species on plant-parasitic nematodes. Veenman and Zonen, NV, Wageningen

Yair A, Rutin J (1981) Some aspects of the regional variation in the amount of available sediment produced by isopods and porcupines, northern Negev, Israel. Earth Surf Proc Land 6:221–234

Zimmer M (2002) Nutrition in terrestrial isopods (Isopoda: Oniscidea): an evolutionary-ecological approach. Biol Rev 77:455–493

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