SOIL MACROFAUNAL ASSEMBLAGE IN SELECTED LANDUSE SYSTEMS IN KERALA:

SPATIAL PATTERN AND STRUCTURAL DYNAMICS

PhD thesis submitted by
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CERTIFICATE

I hereby certify that the thesis entitled "**SOIL MACROFAUNAL ASSEMBLAGE IN SELECTED LANDUSE SYSTEMS IN KERALA: SPATIAL PATTERN AND STRUCTURAL DYNAMICS**" submitted to the Cochin University of Science and Technology (CUSAT), Cochin, Kerala, India for the award of Doctor of Philosophy is a record of original bona fide research work carried out by **Mr. Mujeeb Rahman, P** under my supervision and guidance. This thesis has not been submitted elsewhere for the award of any diploma, degree, associateship or any other similar title to any candidate of this or any other University.

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Place: Peechi
Date: 26|8|2010

Dr. RV Varma
Supervising Guide

DECLARATION

I hereby declare that the thesis entitled **"SOIL MACROFAUNAL ASSEMBLAGE IN SELECTED LANDUSE SYSTEMS IN KERALA: SPATIAL PATTERN AND STRUCTURAL DYNAMICS"** submitted to the Cochin University of Science and Technology (CUSAT), Cochin, Kerala, India for the award of Doctor of Philosophy is a record of independent research work carried out by me under the guidance of Dr. R.V. Varma, Programme Coordinator, Forest Health Division, Kerala Forest Research Institute, Peechi, Thrissur. This thesis has not been submitted elsewhere for the award of any diploma, degree, associateship or similar title.

Place: Peechi
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INTRODUCTION

CHAPTER 1: Introduction

Historically, most of the efforts on biodiversity studies focused, especially on aboveground plant and animal species (Wardle, 2006). However, it is well recognized that in most terrestrial ecosystems, the belowground biota supports much greater diversity of organisms than does the aboveground biota, because soils are the central organizing entities in terrestrial ecosystems (Coleman and Whitman, 2005). As Wolters (2001) opined, "though not apparent to the naked eye, soil is actually one of the most diverse habitats on earth", and is probably one of the species rich habitats of the terrestrial ecosystem which represent a necessary substrate for a large part of global biodiversity (Decaëns *et al.*, 2006). It has been reported that of the total number of described species on Earth (~1,500,000), as many as 23 per cent are soil animals (Decaëns *et al.*, 2006).

Losses of biodiversity and ecosystems functioning due to forest destruction and agricultural intensification are prime concerns for science and society (Dewenter *et al.*, 2007). Landuse-Land Cover (LULC) change is an important dimension of global change, intimately linked to the changes in biodiversity in space and time (Chapin *et al.*, 2000). As Vitousek (1994) notes "three of the well documented global changes are increasing concentrations of carbon dioxide in the atmosphere; alterations in the biochemistry of the global nitrogen cycle; and ongoing LULC change".

Landuse conversion is not an isolated phenomenon. It was reported that (Kumar, 2005) over the last 25 years, rice cultivation in Kerala has come down by 60 per cent, while other major crops like coconut, arecanut and rubber increased by 106, 41, and 627 per cent, respectively. These changes exert great pressure on the natural forests-most of the agroecosystems of today were pristine habitat before a few years back. Habitat fragmentation or separation of landscape into different landuse systems results in numerous, small and disjunctive habitat patches (Fahrig, 2003) and creates mosaics of habitats of different successional stages in landscapes. Knowledge about successional changes in species richness and community composition is essential for understanding biodiversity change in landscapes (Dauber and Wolters, 2005). Conversion of natural systems to modified systems cause a sudden change in the ecology of the systems, leading to shifts in the range of species and local extinctions (Myers and Knoll, 2001) and the loss of species will inevitably have consequences on diversity, community structure and ecosystem processes (Vazquez and Simberloff, 2003). These changes have more profound impact on soil and associated biodiversity, as it receives greater pressure.

No component of ecosystems is potentially more important, both ecologically and economically than soils and their associated biodiversity (Giller *et al.*, 1997). History of soil fauna dates back to pre-historic period. Surprisingly, the study of belowground biological communities and their influence on ecosystem properties is a relatively new field of ecology. During the past 20 years, the importance of soil fauna in the functioning of soils has been recognized and continuously growing as an extension of terrestrial ecosystem (Decaëns *et al.*, 2006). It is only during the past few decades that ecologists have begun to explore belowground communities and their functional significance for plant communities and ecosystem processes (Bardgett *et al.*, 2005a, b). Forest ecosystems are thought to be control systems with relatively high diversity and small change in population structure. Traditional agroforestry systems in the tropics resemble natural rainforests in many structural aspects, and therefore have been suggested to be a promising wildlife-friendly landuse strategy (Nair, 2008). Tropical agroforestry systems hold a significant proportion of tropical rainforest diversity while providing significant economic returns.

National Parks, wildlife sanctuaries, biosphere reserves etc., are established to protect the rich biological diversity. Biosphere Reserve (BR) programme is a concept, aiming to encompass as much as possible of the biological diversity of the planet Earth, and the site should contain unique and pristine biodiversity, ecosystems and landscape suitable to explore and demonstrate approaches to sustainable development and should be appropriate to serve three functions such as conservation, development and logistic support (MoEF, 2007; http://www.unesco.org/new/en/unesco/). As per recent estimates (www.http://en.wikipedia.org, 2009) India has 15 BRs. Recognizing that the Western Ghats is a global biodiversity hotspot, the Nilgiri Biosphere Reserve (NBR) was set up in 1986 as the first BR in India (UNESCO, 2007), and recognized as "Hot Spot of biodiversity" (Myers, 1990; Mittermeier *et al.*, 1999).

Though, agricultural landuse affects large parts of terrestrial area, its contribution to biodiversity conservation is critical for successful conservation in future (Tscharntke *et al.*, 2005; Vandermeer and Perfecto, 2007). Although our knowledge on the biodiversity of organisms in soils is still very poor, soils in the tropics deserve particular attention for a number of reasons. The rate of agricultural intensification in the tropics is greater than in other regions of the world, so that some ecosystems are under threat of major changes or loss of biodiversity. Intensified landuse in agriculture and forestry is irrefutably the main cause of global change and biodiversity loss, though; low-intensity landuse systems are important elements of large-scale conservation programmes (Tscharntke *et al.*, 2005).

The importance of the soil invertebrates may vary with their abundance and taxonomic and functional diversity. Hence a study of soil faunal communities in natural environments can provide a semi-quantitative evaluation; simultaneously comparative study in adjacent disturbed and/or managed systems may point out changes in the abundance and structure of soil invertebrate communities (Lavelle, 1988a, b).

There are also many other reasons for measuring/monitoring soil biodiversity in agricultural land. Soil organisms are critical in determining the functioning of agro-ecosystems (Rossi *et al.*, 2006). It has long been known that soil organisms are integral to soil fertility and soil fauna play a multiple role in soil ecosystems *viz.*, decomposition, nutrient cycling, and water infiltration (Hole, 1981). Sustainable landuse shall maintain soil multi-functionality: biomass production, environmental protection, nature conservation and heritage interests as well as other potential economic uses of soil. Environmental protection measures can have significant impacts on soil biodiversity, but soil biodiversity itself has an essential role to play in many ecosystem services.

Objectives

The study aims to answer fundamental questions on soil fauna biodiversity in the context of rapid landuse changes and intensive land utilization. The major objectives of the study are: inventorying

1. Document major soil macrofauna (earthworm, termite and ant) in selected agroecosystems and natural forests in the Kerala part of Nilgiri Biosphere Reserve.
2. Analyze the distribution pattern of soil fauna in relation to the landuse systems.
3. Evaluate the impact of edaphic and climatic conditions of the habitat on the diversity and abundance of soil fauna.

Scope of the thesis

There is an increasing interest to study soil biodiversity, due to the high diversity and numerical abundance of species living in soil. We lack taxonomic expertise to identify many groups of soil fauna. Also there are various other technical constraints to soil faunal studies in terms of ecosystem functions. Thus adequate measurement and pertinent interpretation is a pre-requisite to interpret the soil biodiversity.

Mosaic concept on soil biodiversity tells that habitat diversity and structural heterogeneity are main drivers of biodiversity in a landscape, which contribute much to the regional diversity also. Though, total species richness of the landscape can serve as a criterion for the sustainable landuse and act as an indicator of change in the community, as said above, it is difficult to assess. One of the possibilities is to find out suitable correlates or surrogates, which can provide a reproducible and comparable estimate of site-specific biodiversity and the result may easily be extendable to other scales. Thus while inventorying the soil fauna, a few macrofaunal groups have been selected namely, ants, earthworms and termites to gather information on site-specific diversity of three ecologically different groups and qualitative information on entire soil macrofauna was collected to study the impact.

It is deduced that an estimate made based on the present result is easily reproducible and result provides insight to the possibility of using selected taxa as a correlate, and versatility as a surrogate of landuse change. Ultimately, the information gathered may help us study the long term change in the soil faunal biodiversity.

Chapter 2

REVIEW OF LITERATURE

CHAPTER 2: Review of Literature

2.1. Background

Biodiversity has received national and international importance in recent times (Myers, 1996; Myers *et al.*, 2000; Sala *et al.*, 2000; Mittermeier *et al.*, 2003), but emphasis is mostly given to the above ground biodiversity. Biodiversity is not only threatened through the accelerated extinction of species, but also through changes in community structure such as the abundance and distribution of species, which may lead to new assemblages on several spatial scales (Kühn *et al.*, 2008). Global change, including multiple human-induced changes to ecological systems, such as climate change, landuse change, biological invasion, urbanization, nitrogen deposition etc., are the major threats to biological diversity (Matson *et al.*, 1997; Sala *et al.*, 2000), but in the case of terrestrial ecosystems, landuse changes probably would account for the largest effect (Sala *et al.*, 2000, Chapin *et al.*, 2000), followed by climate change, nitrogen deposition, biotic exchange, and elevated carbon dioxide concentration. However, attempts are being made to conserve the biodiversity by adopting several measures. Many areas in the world are protected under national parks, wildlife sanctuaries, protected areas, biosphere reserves, etc. Among these, Biosphere Reserves (BR) deserve special attention, because the biosphere reserve was launched under Man and Biosphere Reserve (MAB) programme to conserve the biological as well as the cultural heritage of the region, rather than to protect a single species or habitat.

Owing to multiple reasons, considerable area under forests has been cleared, which have ecological and socio-economic consequences (Jha *et al.*, 2000). It is reported (Jha *et al.*, 2000) that from Kerala alone, about 5000 ha of forest land were lost since independence. As time passed, because of intensive population pressure and due to many socio-economic and political reasons, many of the cultivated areas were converted to monocrop systems like plantations of rubber, coconut or arecanut. Besides, many new landuse types emerged at the expense of natural habitats. This change affected not only the above ground species, but also the belowground ones. Soils in this region are also under intensive pressure, being used for cultivation continuously, with high input inorganic fertilizers and pesticides. In such landscapes, the species composition and richness of soil biota vary depending on the landuse system. Landuse conversion is an unremitting process and an illustrated fact. Perusal of the literature indicates that there had been no attempts made to document the impact of landuse change on soil invertebrate fauna. Though isolated attempts have been made to study the soil invertebrates and their diversity and distribution in different landuse systems (Singh and Singh, 1975; Hazra, 1982; Rossi and Blanchart, 2005), comprehensive information is still lacking on the diversity, pattern of distribution and influence of environmental parameters from a gradient landuse system from tropical countries, especially from India.

An ecosystem can be defined - in terms of the biotic community and its abiotic environment functioning together - as a unit to direct the flow of energy and cycling of materials. Thus the soil ecosystem approach would involve interpreting soil organisms in the context of the soil physical, chemical, and biological attributes inherent in the soil (Fox *et al.*, 2000). Soils are complex heterogeneous environment, and belowground environment provides numerous niches to soil fauna concerning microhabitats, microclimatic properties, soil chemical properties, and phenologies of the organisms themselves (Wardle, 2002; Coleman and Whitman, 2005).

2.2. Importance of soil fauna as a component of ecosystem

Over 50 per cent of the Earth's species are confined to the tropical latitudes, as many as 44 per cent of all species of vascular plants and 35 per cent of all species in four vertebrate groups are confined to 25 hotspots comprising only 1.4 per cent of the land surface of the earth (Myers *et al.*, 2000). But the hotspot largely omitted invertebrates, which is undocumented in many areas, and if available, the data mainly was focussed on the above ground species.

Soil macrofauna are conspicuous animals on the earth, but largely a neglected group. It is known that, soil fauna play a critical role in the biological turnover and nutrient release from plant residue. Hole (1981) identified different kinds of activities by which soil organisms influence the soil. This include mounding, mixing, forming and back filling voids, forming and destroying peds, regulating soil erosion, movement of water and air in the soil, plant and animal litter decomposition, nutrient cycling, and producing special constituent through process of regurgitation, mixing of saliva or excreta with soil materials. Later, Lal (1988) reviewed the effect macrofauna on rates of soil turnover, mineralization and humification of soil organic matter, soil texture, total porosity, water infiltration and soil water retention in tropical ecosystem. The community structure, functional attributes, spatial and temporal pattern of soil macrofauna are complicated and so little are understood.

Recently, a number of studies have been carried out in temperate as well as in tropical soils to demonstrate the role of soil fauna in soil health, soil ecological classification as indicator species, their role in ecosystem processes, and sustaining crop productivity (Lavelle, 1996; Brussaard *et al.*, 1997; Smith and Bradford, 2003;Hättenschwiler and Gasser, 2005). Different types of organisms have different activities in the soil like, predators (*e.g.*, protozoa, nematodes, centipedes), litter transformers (*e.g.*, earthworms and enchytraeids), ecosystems engineers (earthworms, termites, ants) and more. The interaction among animals, plants, microbes, and soil biota is of relevance IN topic in soil ecology.

Since soil organisms in the soil participate significantly in the process of soil formation, function and maintenance, soil fauna serve as a sensitive indicator of prevailing soil condition. The biomass of fauna is relatively small in proportion to the total soil mass, yet the activity of these animals is very important in altering the soil fabric and micro-topography, changing the distribution and assemblage of soil materials as well as organisms.

2.2.1. Definition for soil fauna

Soil biodiversity (=Belowground Biodiversity-BGBD) is a collective term referred to all the living forms in soil and litter. It includes the soil flora and soil fauna. Besides, it is difficult to give an accurate definition for soil organisms, because there are "fulltime" (earthworms, macro-invertebrates and many micro and meso arthropods) and "part-time" (insect larvae, mound building insects) inhabitants (Wolters, 2001). It is better to adopt a *sensu lato* definition because the limit of 'soil habitat' is difficult to discriminate.

2.2.2. Diversity of soil fauna

Although soil is one of the species rich habitats of the terrestrial system, total estimate on the number of species in soil is still lacking due to many reasons. Majority of terrestrial animals are soil inhabitants for at least one stage of their life cycle (Andrén *et al.*, 1999; Wolters, 2001) and a rapid survey of invertebrates and vertebrate group reveals that about ¼th of described living species are strictly soil or litter dwellers (Decaëns *et al.*, 2006). Out of the 1,500,000 described living species, soil fauna represent 23 per cent (*i.e.*, ~360,000); of which 80 per cent are insects and 12 per cent are arachnids. There may be a number of reasons for this tremendous diversity, but trophic niche partitioning, spatial and temporal segregation, higher diversity of micro-habitats etc., could be the important reasons for such a large number of co-existing species (Giller, 1996; Wolters, 2001). Despite its supposedly critical contribution to the global biodiversity, soil fauna has received little taxonomic attention compared to other groups.

2.2.3. Classification of soil biota

In general, soil fauna is classified as macro, meso and micro-fauna based on their body size and epigeic, endogeic or anecic, by considering the ecological features. The easiest and most widely used system of classifying soil organisms is by their body size. They are divided into three groups: micro, meso and macrobiota (Wallwork, 1970., Swift *et al.*, 1979).

The macrobiota are generally >2mm in diameter and visible to the naked eye. Invertebrates live and feed in or upon the soil, surface litter and their components include ants, termites, millipedes, centipedes, earthworms, pill bugs, beetle larvae, caterpillars, cicads, ant-lions, earwigs, silverfishes, snails, spiders, scorpions, fly and wasp larvae, cockroaches, etc., together considered as macrofauna. Mesobiota are organisms ranging from 0.1-2mm in diameter and include mainly microarthropods like spring-tails, diplura, protura, mites, pseudoscorpions, myriapods like pauropoda and symphyla and worms like enchytraeids. They have limited burrowing ability and live within soil pores, feeding on organic matter and microflora. Microbiota are the smallest organisms <0.1mm, extremely abundant, ubiquitous and diverse. The microflora include algae, bacteria, archaea, cyanobacteria, fungi, yeast, myxomycetes and actinomycetes and they are able to decompose almost any existing natural materials. The microfauna include nematodes, protozoa, turbellarians, tardigrades and rotifers and they generally live in the soil water films and feed on microflora and plant roots.

Soil invertebrates can be classified according to their feeding habits and distribution in the soil, *i.e.*, by considering the functional aspects (Swift and Bignell, 2001) *viz.*, epigeic species, anecic species and endogeic species. Epigeic species are 'surface-active' biota which live and feed on the soil surface. These invertebrates affect litter comminution (reduction in litter size) and mineralization (nutrient release), but do not actively redistribute plant materials. They include arthropods *e.g.*, ants, beetles, cockroaches, centipedes, millipedes, woodlice, orthopterans (grasshoppers), gastropods (snails) and small, entirely pigmented earthworms. Anecic species feed litter from the soil surface and transport it to the deeper soil layers. Through their feeding activities, considerable amount of topsoil, minerals and organic materials become distributed through the soil profile; this is also accompanied by channel or structure formation and an increase in soil porosity. This group includes earthworms, non-soil-feeding termites and arachnids (spiders). Endogeic species are organisms which live in the soil and feed on organic matter and dead roots and ingest large quantities of mineral materials. Fauna included in this group are non-pigmented earthworms and soil-feeding termites.

2.2.4. Soil biota in ecosystem processes

In addition to plants, soil is the habitat of a diverse array of organisms and activities of which contribute to the maintenance and productivity of agroecosystems by influencing soil fertility (Hole, 1981; Lavelle, 1996; Brussaard *et al.*, 1997). Soil biodiversity has a crucial role to play in mediating other soil functions. This includes environmental protection by retaining and breaking down pollutants, carbon, nitrogen and phosphorous compounds; stabilizing soil, enabling water percolation and incorporating organic matter. All these activities serve to protect soil against erosion, aid in restoration of degraded land, maintain water quality and increasingly, influence carbon sequestration and reduction of trace gas emissions (Lavelle, 1996).

Soil ecosystem services are reliant upon soil biota mediated functions at very fine local scales. These functions are referred to as the indirect value of soil biodiversity and include soil formation and nutrient cycling. Studies indicate that soil macrofauna can increase the translocation of organic matter (Frouz *et al.*, 2006), which channelize other processes in the soil. These fundamental processes facilitate services that benefit humans such as primary production, agricultural productivity and regulatory services including carbon sequestration and control of greenhouse gas fluxes. Some species are valuable source of protein for indigenous populations in many regions of the world (Gullen and Cranston, 2005).

Earthworms are well known for their ability to influence soil structure and fertility as well as plant production and community structure (Lee, 1985; Lavelle, 1988b; Curry, 1994; Edwards and Bohlen, 1996). Introduction of earthworm is a common practice where they are lacking, especially in agricultural fields. Termites can be considered as herbivores and/or decomposers as they eat, almost exclusively, dead plant material. Either way, termites are one of the few organisms that have evolved the capacity to digest the molecules used to build plant cell walls: cellulose and lignin. Consequently, termites are among the most important nutrient recyclers, particularly in warmer environments and arid regions. Perhaps the key to their successful expansion was their ability to build specialized nests with a warm, moist homoeostatic internal environment, similar to that of a tropical rainforest. Termites also humify the soil and it has been proposed that termites may play an important role in plant growth and vegetation structure (Black and Okwakol, 1997; Dawes-Gromadzki, 2005).

Termites affect soil moisture in two ways: passively and actively. Tunnels made by termites are conduits through the soil for surface water, especially rain water. Termite tunnels increase soil macroporosity and water infiltration relative to soil type (particularly for abandoned nests). The removal of subterranean termites has been shown to reduce water infiltration by 80 per cent in fallow agricultural plots (Sarr *et al.*, 2001) and by 48 per cent in desert ecosystems due to gallery collapse and an increase in soil density (Elkins *et al.*, 1986). The relocation of soil particles for mound construction and maintenance influences topography and soil physical properties as well as spatial patterns of nutrient availability. Termites have been estimated to turn over 300-400 kg ha^{-1} of soil annually (Coventry *et al.*, 1988). Mound building termites have an extended period of impact on soils compared to the more transient effects of most other soil biota

Soil-nesting ants may be extremely prolific and afford extensive macroporosity to the soil to improve water infiltration rates and the movement of nutrients through the soil profile (de Bruyn and Conacher, 1990). The potential influence of ant colonies on the transfer of water and nutrients to groundwater and adjacent ecosystems has not been explicitly investigated; however, bulk flow along colony galleries has been shown to be important in deep soil moisture level (de Bruyn and Conacher, 1994). In addition to enhance the movement of water and nutrients through soil, many species collect and transport live or dead animal and plant materials into the nest. This behavior invokes chemical alteration of the soil profile whereby soil nutrient content may be increased depending on the amount and type of organic matter incorporated (de Bruyn and Conacher, 1990). In addition to soil engineering effects, ants are also known to be highly effective in the dispersal of seed (*i.e.*,myrmecochory). Myrmecochorous seed removal and dispersal plays a key role in vegetation dynamics worldwide and is considered successful for the plant if the ants transport the seed back to the nest, remove the elaiosome (a nutrient-rich food reward for the ants) and then discard the seed outside the nest.

Due to the building of below-ground galleries, mounding and material mixing, the soil of ant nests is characterized by the impeded formation of soil horizons, increased porosity, drainage and aeration, reduced bulk density and modified texture and structure. Increased content of organic matter, P, N and K in the nests is due to food storage, aphid cultivation, and accumulation of faeces and ant remains (Hole, 1981; Lavelle *et al.*, 1997; Folgarait, 1998). A study conducted by Dostál *et al.* (2005) on the effect of ant-induced soil modification and its effect on plant below-ground biomass in mountain grassland showed that increased concentrations of available P and K in the nests, concentrations of total C, total N, Ca^{2+} and Mg^{2+} were lower. The result was also cross checked with occupied and abandoned nests in which the soil fertility of abandoned nests was similar to the surrounding soil. Besides, there was also modification in the soil physical properties in the ant worked soil.

Earthworms were most abundant invertebrate macrofauna (Critchley *et al.*, 1979) in many areas of the world, the overall dry mass of soil ingested by earthworms often reaches 500-1000mg/ha/yr (Lavelle, 1988a). At the same time humivorous termites ingest 45mg dry soil/year/ha. The estimated annual soil turn over by ants in semiarid regions was 350-420 Kg/ha/year (de Bruyn and Conacher, 1990). Earthworms, termites and ants together contribute to the maintenance of a relatively high porosity by digging galleries and these galleries help not only water infiltration but gas diffusion also.

Earthworm contributes to soil aggregation mainly through the production of casts; ants through their burrows, which contribute to aggregate stability, gas and water infusion. Thus it can be concluded that earthworm, termite and ant are significant determinants of pedogenetic processes in the upper 30-60cm of soil (Lee and Wood, 1971).

Lavelle (1997) and Lavelle *et al.* (1997) explained the role of invertebrates on Soil Organic Matter (SOM). They increase the decomposition rate of litter (Tian *et al.*, 1995) and alter the pH to slightly basic and enrich soil with organic carbon, total nitrogen, Ca, Mg, K, and Na by digesting and decomposing plant material.

2.3. Soil faunal studies-past attempts and present status

In pre-historic, probably from the Magdalenian Cultures (25,000-30,000 years ago) and ancient civilizations (Sumerian and Egyptian, 2000-3000 years ago), different animals of the soil fauna such as beetles were represented and appeared in various man-made articles (see Warkentin, 2006 for review). During that time, such representations were much associated with veneration or superstition or belief. It is now known that in ancient Egyptian civilization, scarabaeids, in particular those commonly called "Dung beetles" were considered as sacred (or venerable) animals, because "it pushed or brought the sun between its legs" when it rolled and then buried balls of vertebrate fecal material in which the female lays her eggs. The Greek, Aristotle (384-344 BC) called the earthworms, "the intestine of the earth" by observing their behavior and Egyptian queen Cleopatra (69-30BC) instituted a law to forbid the export of earthworms. It was only recently, at the end of the 19th century that a real interest was shown in soil biology, for both soil fauna and soil microorganisms. Before the end of the 19th century "soil biology" was considered as part of soil science, which was focused mainly on plant growth.

During 1750 to 1860, which can be considered as a second historical period, studies on soil biological process was focused on plant nutrition and plant growth *i.e.*, on agronomic problems and was developed using field experiments, pot experiments, and chemical analysis of plants, air and soils. During this time concept of plant nutrition, soil enzymes and nutrient cycling, pollution, soil microbes, and interaction among microbes, microbes and fauna have been studied at various depths.

Darwin (1881) was the first to observe, propose and emphasize the role of soil fauna (*i.e.*, earthworms, termites and enchytraeids) in the transformation of organic matter originating from plant root and litter and in humus formation in soil. Until after the middle of the 20th century different groups of fauna in soil, *e.g.*, nematode, gastropoda, lumbricidae, arthropoda, oligocheta, crustacea, myriapoda, and insects like collembola, termites, diptera, and coleoptera were studied mainly by taxonomists-more from a taxonomic and biological point of view than from an ecological and/or functional point of view (Bachelier, 1978; Dindal, 1990). Soil zoology truly developed as a discrete discipline during the last five decades. After 1950s a rapid progress in the soil faunal studies, witnessed due to the important contribution of Macfadyen (1957), Kevan (1955, 1962), Farb (1959), Doeksen and van der Drift (1963), Burges and Raw (1967), Graff and Satchell (1967), Wallwork (1976), and Lebrun *et al.* (1983). These authors have drawn together a considerable amount of information on the general biology and ecology of soil fauna, and have done much to stimulate interest in this field.

Simultaneously, selective methods for extraction of soil fauna were developed. Berlese device in 1905 enabled the recovery of a large proportion of these animals. The technique was simplified and improved by Tullgren in 1918 and the device is often called as Berlese-Tullgren funnel. In the second part of the 20th century, integrated concepts and approaches on interaction between different organisms, meso, macro and microbiota and with the soil constituents emerged and developed. During the same period, scale concept has also been seeded and provided results on the specific activities of representative groups of soil fauna.

2.3.1. Soil faunal studies in India

Studies on soil faunal taxonomy from Indian sub-continent dates back to 19th century; commendable work was done by Bingham (1903) on ground dwelling ants and Imms (1912) on collembolans. An exhaustive review on soil fauna was given by Singh (1978). At the same period, symposia on "Soil Biology and Ecology in India" (Edwards and Veeresh, 1978) and "Progress in Soil Biology and Ecology in India" (Veeresh, 1981), followed by "Applied Soil Biology and Ecology" (Veeresh and Rajagopal, 1983) and "Advances in

Management and Conservation of Soil Fauna" (Veeresh *et al.*, 1991), signaled the gradual maturity of soil faunal studies in India. Added to this venture was the launching of the Indian Journal of Soil Biology and Ecology in 1981. Many articles on soil fauna were published in the succeeding issues of this journal, which enriched the database on soil biodiversity and ecology in India.

2.4. Soil macrofauna as ecosystem engineers

As the total diversity of organisms is too large to quantify or classify (Hairiah *et al.*, 2001), ecologists often use the concept of 'functional groups', for groups of soil organisms that contribute to ecosystem functioning in a similar way (Brussaard, 1998). Ecosystem engineers are organisms that directly or indirectly modulate the availability of resources to other species, causing physical state changes in biotic or abiotic materials (Jones *et al.*, 1994, 1997). The ecosystem engineering concept focuses on how organisms physically change the abiotic environment and how this feeds back to the biota.

Large as well as abundant invertebrates ingest or manipulate both organic and mineral materials and create long-lasting microstructures in the soil. These invertebrates are designated as soil ecosystem engineers. It is argued based on numerical and biomass attributes, density, geographical distribution and known functional roles that earthworms and termites are the most important engineers in terrestrial ecosystems. Evidence is presented that they may exert influence on the diversity and activity of biota in subordinate trophic levels.

In a broader sense, ants are also considered as soil engineer because they also affect the soil properties and their influence on the availability of resources for other organisms, including microorganisms and plants (Jouquet *et al.*, 2006). Like other organisms, activities of ants affect soil structure through ingestion of mineral and organic matter, digestion process which modifies the organic component, egestion as faecal pellets and organo-mineral aggregates, building long lasting chambers and galleries (Wood, 1996; Lavelle, 1997; Lavelle *et al.*, 1997). At the heart of the soil engineering concept is the ability of these organisms to move through the soil and to build organo-mineral structures with specific physical, chemical and microbiological properties (Lavelle *et al.*, 1997).

Soil fauna creates network of pores by aggregation of soil particles. Earthworms, termites and some ants can create macropores by pushing their bodies into the soil (and thus compacting a zone of soil around the channel that can persist for some time), or by eating through the soil and removing soil particles. Earthworms and other animals that feed on soil produce excrement that contains resistant organo-mineral structures that may persist for long periods of time (from months to years) and which profoundly affect the environment for smaller organisms. Earthworms and termites can do this because they have a gut flora of bacteria. These activities of soil biota, which include moving particles from one horizon to another and which affect and determine the soil's physical structure and the distribution of organic material in the soil profile, are termed 'bioturbation', which in turn can have an effect [illegible] plant growth. Actually, process of bioturbation was first published more than two centuries ago (Darwin, 1881), which now have an important dimension (Meysman, 2006).

2.4.1. Earthworm, Termite and Ant

Earthworm (Annelida:Oligochaeta), Termite (Insecta:Isoptera) and Ant (Hymenoptera: Formicidae) are the important faunal groups in the soil. Earthworms are considered to be the most beneficial organisms they are often called "natures ploughman" (Darwin, 1881). According to Römbke *et al.* (2005) earthworms are the most important soil invertebrates in most soils worldwide, in terms of both biomass and activity, but their relative importance may vary from location to location and nature and objective of the work. According to James (2000) there are about 4300 species of earthworms world wide and 505 species are reported from Indian region (Blakemore, 2006). Though scattered information on these groups from the tropical regions are available, comprehensive information on the diversity and composition of soil organisms with reference to different landuse systems is lacking. The population dynamics of earthworms and its relevance to the nutrient cycling have been reported from the north-east India (Bhadauria and Ramakrishnan, 1989, 1991). Information is also available on the diversity, density and distribution of earthworms of Tamil Nadu (Ismail and Murthy, 1985; Ismail *et al.*, 1990) and Karnataka (Kale and Krishnamurthy, 1981; Bano and Kale, 1991).

Three major functional groupings for earthworms are made by their feeding and burrowing behavior: epigeic species live in the upper litter layer and feed on coarse particulate organic matter, endogeic species live throughout the upper soil layers mixing mineral and organic soil horizons, and anecic species (which are commonly large) are deep-burrowing and feed on surface litter that is pulled into the burrow from one or more soil surface openings. In Kerala, major contribution of exotic earthworm by *Pontoscolex corethrurus,* an endogeic worm, has a highly efficient digestive system and exceptional demographic traits, allowing it to quickly colonize disturbed places, from where native earthworms have been expelled (Lavelle and Pashanasi, 1989).

Lee and Wood (1971) reported that, diversity of termites (Isoptera) was at maximum in tropical rain forests, but the level of activity appears to be highest in deciduous woodlands. They also noticed the functional diversity of the termites and their ability to digest cellulose and hemi-cellulose in ingested litter. Studies carried out using the transect protocol showed that termite richness and abundance are inversely proportional to the canopy cover (Jones and Eggleton, 2000; Jones *et al.*, 2005). Termites are the most important decomposers by virtue of their numerical dominance of the belowground community (Eggleton *et al.*, 1995, 1996). Estimates (Dibog *et al.*, 1998) indicate that about 2750 species coming under 285 genera have been identified worldwide. A study conducted by Basu *et al.* (1996) in the Western Ghats reported 12 species of termites coming under 9 genera and their result showed that natural forest harbors more species (total of 10 species) than the disturbed area. Varma and Swaran (2007) made a study in a tropical forest plantation to identify the pest and non-pest species of termites. Out of the 14 species of termites collected, only four species were found as pest species and the remaining species had only positive ecosystem functions.

Termites can be classified according to the type of plant material they eat, *i.e.*, wood, litter, grass and soil organic matter. Wood feeding is the most primitive; *e.g.*, all 'lower-termites' (those species that have symbiotic gut protozoa as well as archaea and bacteria) eat only wood, whereas soil feeding is the most derived (higher termites). The factors that influence termite diversity are debated intensely, but geography and evolutionary time are certainly important (Davies *et al.*, 2003).

Ants form another major component of soil organisms and also on litter in the forest floor. Ants have the peculiar habit of manipulating and modifying their immediate surroundings. They change physical and chemical parameters of the soil by bioturbation and by accumulation of organic material (Dostál *et al.*, 2005).

The family formicidae includes about 15,000 living species, of which >10,000 have been described (Bolton, 1994). In India, about 582 species are present (http://www.antdiversityindia.com/). A study conducted by Gadagkar *et al.* (1993) in forests and in monoculture plantations in the Karnataka part of Western Ghats reported 120 species coming under 31 genera and SunilKumar *et al.* (1997) collected 75 ant species belonging to 33 genera from different habitats in Bangalore and their result showed that monoculture plantations showed least diversity. Study by Ribas and Schoereder (2007) showed that ant species richness did not respond to tree density, but increased with structural heterogeneity. Species composition was affected both by tree density and structural heterogeneity. Moreover ants are proposed as a good candidate bioindicator (Andersen, 1997; Andersen *et al.*, 2002) of ecosystem stress and disturbances. The use of ants as bioindicators supported by a macro scale functional group scheme is often practiced (Andersen, 1993).

2.5. Characterization of soil fauna

A soil ecosystem approach would involve interpreting the activity of soil organisms in the context of physical, chemical and biological attributes of the soil (Fox *et al.*, 2000). The intensity, duration and interaction of these processes will influence the biodiversity within soil. Characterization of soil biodiversity usually is a three step process (Fox *et al.*, 2000), which ease the sampling and interpretation of data as part of ecosystems approach and easily reproducible. They are: (1) Characterization function: a set of attributes are identified which uniquely describe the components of the ecosystem, (2) Diagnostic function: the effect on the inherent biodiversity from environmental and anthropogenic influences which can be interpreted in terms of the dynamics of the ecosystem processes and abiotic and biotic interactions and (3) Predictive capabilities: trends and variations in the inherent biodiversity can be predicted in relation to the spatial and temporal changes occurring in abiotic and biotic factors as a result of environmental and anthropogenic impacts on ecosystem processes.

Environmental predictors can exert direct or indirect effects on species, arranged along a gradient from proximal to distal predictors (Austin, 2002) and are optimally chosen to reflect the three main types of influences on the species (Guisan and Zimmermann, 2000; Guisan and Thuiller, 2005): (i) limiting factors (or regulators), defined as factors controlling species physiology (*e.g.*, temperature, water, soil composition); (ii) disturbances, defined as all types of perturbations affecting environmental systems (natural or human-induced) and (iii) resources, defined as all compounds that can be assimilated by organisms (*e.g.*, energy and water). These relationships between species and their overall environment can cause different spatial patterns to be observed at different scales (Guisan and Thuiller, 2005).

Assessment of biodiversity in managed landscapes remains a problem mainly for two reasons (Waldhardt, 2003). (i) Diversity measures strongly depend on the chosen spatio-temporal scale of the prevailing assessment, and unfortunately there are no satisfying scaling functions applicable to transfer results to another scale. (ii) Relations between biodiversity and land-use are generally very complex (Szaro and Johnston, 1996). Besides "natural" (*e.g.*, geological and climatic conditions) and "anthropogenic" (*e.g.*, specific management practices, habitat fragmentation) environmental conditions, ecological processes and socio-economic factors also have to be taken into account.

2.6. Spatial segregation of soil fauna

The soil fauna are distributed unevenly in the soil. The factors causing non-randomness is presumably related to the patchy distribution of food or water, which cause aggregation (Usher, 1976; Usher *et al.*, 1982). In soil biodiversity studies it is essential to know not only which species are present, but also where the species occur in relation to one another (Coleman and Whitman, 2005). Whether species occur together at every micro-site, or do they occur individually in separate site is of great relevance. This aspect of species distribution has an important bearing on competition and other interactions, with functional consequences to the ecosystem (Coleman and Whitman, 2005). Traditionally, soil communities are considered to be saturated communities in which the biotic interactions between species and trophic groups are intense (Setälä *et al.*, 2005). But land-use change creates mosaics of habitats of different successional stages in landscapes and knowledge about successional changes in species richness and community composition is essential for understanding biodiversity change in landscapes (Dauber and Wolters, 2005). Soil communities in landscapes are rapidly changing due to land use change, and can be regarded as highly transient systems where interactions between species or trophic levels may be seriously disturbed or possibly lost (Hedlund *et al.*, 2004). Though habitat quality may be the most important factor determining the presence of a species at a given site (Duelli, 1997), diversity within a patch additionally depends on the structure of the surrounding landscape.

During the past decade many authors have analyzed the spatial distribution of soil fauna (Jiménez *et al.*, 2001; Hernández *et al.*, 2007). Communities of soil invertebrates show generally a high degree of spatio-temporal organization (Jiménez *et al.*, 2006). Soil biota have long been known to be spatially aggregated, but recent studies have more precisely noted the various scales of spatial patterning (Jiménez *et al.*, 2006). The factors that contribute and control these patterns are largely unknown and difficult to identify as spatial distribution originates from both environmental (biotic and abiotic) and internal community or population factors (Robertson and Freckman, 1995). Indeed general habitat quality and resource availability regulate distribution and diversity of soil fauna, abiotic and biotic factors play a crucial role. Species utilize resources from their immediate surroundings; a change in the environmental condition affects the species, either positively or negatively.

Besides, unlike the above ground species, due to their limited mobility, soil-dwelling invertebrates are likely to be affected more seriously by any change in the factors acting upon it. There are a number of studies, which demonstrate the effect of both abiotic and biotic factors on soil fauna.

2.6.1. Stress and Disturbances

The disturbances influence soil communities mainly on a local scale, but it is the result of large-scale processes, such as changes in land use, fragmentation of the original landscape and changes in the distribution patterns of organisms (Brussaard *et al.*, 1997; Schröter *et al.*, 2004). Although many studies on effect of disturbance on soil fauna have been published, effect of certain disturbance gain over-emphasis. Commonly, studies on effects of disturbances have concentrated on single "pulse disturbances", focused on immediate and short-term effects. Many researchers studied the effects of, *e.g.*, pollution, pesticides and fire on soil fauna (Barrett, 1968; Metz and Farrier, 1973; Merrett, 1976; Strojan, 1978; Tamm, 1986; Bengtsson and Rundgren, 1988; Hoy, 1990; Haimi *et al.*, 2000; Haimi and Mätäsniemi, 2002; Sileshi and Mafongoya, 2006). Studies on effect of climate-related disturbances on soil fauna are fewer, but include effects of drought and icing (Coulson *et al.*, 2000; Frampton *et al.*, 2000a, b; Pflug and Wolters, 2001). Disturbances and associated stress may arise by various reasons. Agricultural practices like tilling, sloughing, slash and burn etc., are of immediate concern. Adverse effect of deep tilling on insect larvae has been reported (Oliveira *et al.*, 2000). Impact of logging, fire and associated stress are important reason for reduced soil fauna and well documented (Basu *et al.*, 1996; Vasconcelos, 1999; Gathorne-Hardy *et al.*, 2002; Castan O-Meneses and Palacios-Vargas, 2003; Gillison, *et al.*, 2003; Jones *et al.*, 2003; Bickel *et al.*, 2006; Donovan, *et al.*, 2007). A study by Sileshi and Mafongoya (2006) reported that the total number of higher taxa per sample and the population density of certain groups like annelida, chilopoda, arachnida and some hexapoda were low under burnt forest patches, compared to unburnt area. Similar type of observation was also made by Apigian *et al.* (2006) and they showed that fire affect beetles and other litter associated fauna. It is also interesting to note that even after 6 to 12 years, negative impact of selective cutting and strip clear cutting is persisting which affect the abundance of soil fauna. Change in the community structure of land snails was observed due to disturbances (Martin and Sommer, 2004).

As the impact on a community is also dependent on the duration and the spatial scale of the disturbance, it is important to conduct more studies with different temporal and spatial disturbance regimes, but there is lack of information on effects of repeated and large-scale disturbances on communities and ecosystems (Paine *et al.*, 1998; Romme *et al.*, 1998).

Bhadauria and Ramakrishnan (1991) found earthworm communities in temperate forests of northeast India composed of three native endogeic species and after slash and burn practices were imposed, the community lost two native species, but at the same time two other species invaded (one native and one epigeic exotic). But a regional survey undertaken by Bano and Kale (1991) in southern Karnataka revealed that native species were well adapted to agroecosystems. From a total number of 44 species (36 natives and eight exotics), 25 native species were found only in managed ecosystems. The reason for this adaptation is not clear, but it could be related to the prevalence in the region of low input agricultural practices and to the fact that most of these earthworms are endogeic species which are more resistant to changes in land use practices. Blanchart and Julka (1997) studied earthworm communities from undisturbed forests to extensive pastures. Their result showed that earthworm communities were composed mostly of endogeic species, with only one epigeic species being found (from a total of 30 species). Of the 26 species found in the forests, ten species disappeared in disturbed sites, whereas the remaining species were able to survive in at least one type of agroecosystems.

2.6.2. Chemical Fertilizers and Pesticides

Pesticides and fertilizers are integral part of agriculture and studies related to their impact are well documented. Pesticides like Aldrin and DDT (Edwards and Dennis, 1960), metal pollutants (Sun *et al.*, 2007) have adverse impact on soil fauna, resulted in decreased density, diversity and evenness of soil biota. Similar result was also obtained by Spurgeon *et al.* (2008) and showed that Zn badly affects the soil fauna. Air borne pollutants also have a negative effect on soil fauna (Rusek, 2000).

Airborne pollutants affect soil organisms both directly and indirectly. Direct toxic effects are associated with uptake of free acidic water from the environment by soil fauna and with consumption of polluted food materials by others. Indirect effects are mediated primarily through disappearance or reduction of the food resources such as microflora and microfauna of soil animals, changes in organic matter content and modification of microclimate. In the field, changes in competition among species were probably an important factor that influenced the soil faunal community structure as well as the reactions of individual species to soil acidification or liming. The overall effect is depauperation of soil with an attendant reduction in the rate of organic matter decomposition.

Fertilizer application and associated practices also affect the soil organisms

(McLaughlin and Mineau, 1995). The impacts on soil fauna of high doses of fertilizers applied for a prolonged time is poorly known (Abrahamsen and Thompson, 1979). But studies by Lindberg (2003) show that prolonged fertilizer application have negative impact on soil fauna, lime addition may also reduce the fauna like earthworm and enchytraeid population (Cole *et al.*, 2006). It is possible that many negative effects persist, but a community stabilization over time could also occur through colonization of resistant species or responses in the soil biota (plants or fungi), which may reduce the impact on the communities.

2.6.3. Effect of moisture and temperature

Effect of temperature and moisture content on soil fauna was studied by Abrahamsen (1971). Temperature and moisture content of the soil play a critical role in the distribution and diversity of soil organism. Many soft-bodied organisms like earthworms are sensitive to desiccation during dry conditions (Ismail *et al.*, 1990; Ganihar, 1996; Karmegam and Daniel, 2007). Soil fauna undertake vertical movements deeper into the soil or redistribute to moist patches to avoid drought. They can also enter into inactive stages, or survive as dormant eggs, which are reactivated when sufficient moisture level is achieved. Heavy rains or flooding may lead to waterlogged conditions that cause mortality of soil fauna.

2.6.4. Succession and dispersal of soil fauna

Habitat is a key element in understanding the population dynamics and distribution of plants and animals (Morris, 2003), and there is positive relationship between abundance and distribution, most common species in a taxon or assemblage tend to be the most widely distributed also (Hanski, 1982; Brown, 1984; Gaston, 1996; Gaston *et al.*, 2000). When intensively utilized landuse is converted to less intensive type landuse (for *e.g.*, agriculture system to agroforestry system), the landuse may restart 'succession' from the previous stage to a new stability domain. Re-establishment or reorganization after release from disturbance or stress may take a long time and is influenced by spatial heterogeneity of resources available in the new habitat. The new landuse type formed may provide better habitat for soil fauna, as it lack disturbances or have more resources, which accelerate colonization of soil fauna.

Parthenogenesis may for example facilitate a quick population establishment after a disturbance (Norton, 1994), although the relation between such life-history traits and colonization succession is not always clear-cut (Baur and Bengtsson, 1987; Ås *et al.*, 1992).

The recovery process of soil fauna following climatic disturbances has seldom been studied, but there are many studies on colonization of man-made habitats (Hutson, 1980; Davis, 1986; Judd and Mason, 1995; Verschoor and Krebs, 1995; Wanner and Dunger, 2002). Post-fire recovery of communities has also received much interest (*e.g.*, Huhta, 1971; Merrett, 1976; Tamm, 1986; Webb, 1994).

Good dispersal ability may enable a species to quickly re-colonize an area after a disturbance (Grubb, 1987; Bengtsson and Baur, 1993). Dispersal rates are low for soil organisms relative to above ground biota (Compton, 2002), and we know very little about the dispersal abilities of many species of soil fauna (Ojala and Huhta, 2001). Poor dispersal rates probably characterize many microarthropod species (Norton, 1994; Petersen, 1995; Sjögren, 1997; Ojala and Huhta, 2001), large soil arthropods, such as beetles and spiders, are mobile and use locomotion or dispersal by air (Merrett, 1976; Dindal, 1990). Other species may survive in low densities at a site and are able to respond quickly to better conditions. Special microhabitat preferences or an ability to withstand environmental stress are adaptations for this "survivor" strategy.

Most soil organisms are generally believed to require long periods of time to actively colonize new areas, as in succession of former agricultural land (Scheu and Schultz, 1996; Korthals *et al.*, 2001). Although most soil organisms have effective dispersive and colonizing abilities, the actual time frame for establishment of a functional community is tens of years (Purtauf *et al.*, 2004). Agricultural landscapes are characterized by a very high spatial and temporal heterogeneity determined largely by human activities and little is known about how species are affected by such heterogeneity and how they persist in agricultural systems (Di Giulio *et al.*, 2001).

2.7. Threats on soil faunal biodiversity

There are many causes for vulnerability of species to extinction, which include adaptive strategy of species, abundance of species, geographical range and adaptability of species to particular habitat (Primack, 2000) and most of this attributes are interdependent. Physical factors, modification of vegetation, conversion to agro-ecosystems also catalyse changed community structure (Decaëns *et al.*, 2006).

2.7.1. Landuse change and intensive land utilization

Conversion of natural vegetation to agroecosystems and intensified agriculture has profound impact on soil fauna, because it changes the vegetation and soil micro-climate.

Soil fauna community perfectly fit Hutson's dynamic equilibrium model (Hutson, 1996), where community diversity is maximum when productivity and perturbation are in equilibrium. But in managed landscapes, this equilibrium may be disrupted, by various disturbances.

Deforestation and associated landuse changes have great significance on belowground biodiversity. In India, the Eastern Himalayas and the Western Ghats constitute two of the 24 global hotspots of biodiversity which harbour most of the biodiversity of the country. The rate of habitat loss in this area is alarming. Prasad *et al.* (1998) have assessed 0.90 per cent annual decline in natural forest cover in Kerala for the period 1961-1988 while, Menon and Bawa (1998) have estimated the rate of deforestation in the Western Ghats to be 0.57 per cent annually during the period 1920-1990. Though there are contradictions, deforestation is a reality and is going on. Recent reports indicate that deforestation rate is higher than the figures estimated earlier (Jha *et al.*, 2000).

There are many recent studies to show that landuse type influences the soil invertebrate communities. Study conducted in the Western Ghats (Rossi and Blanchart, 2005) shows that the soil macrofauna density varied distinctly across space and time. Ants, earthworms and termites are more dominant taxa in the area. Mean macrofauna density were high in forest sites sampled. Dangerfield (1997) also showed that soil macrofauna varied across different habitat, more abundant in closed canopy area.

There are number of landuse and landscape features like, land management and soil moisture (Martin and Sommer, 2004), forest perturbation and the diversity of tree ecosystem (Nestel *et al.*, 1993), "edge effect" (Dauber and Wolters, 2004), landscape effect, like surrounding patch-boundaries and grasslands (Öberg *et al.*, 2008), topographic heterogeneity (Gebeyehu and Samways, 2006), type and vegetation structure (David *et al.*, 1999), landuse intensity and local habitat properties (Schweiger *et al.*, 2005), etc., affect the diversity and distribution of soil biota. A case study (Mathieu *et al.*, 2004) to demonstrate the influence of three spatially hierarchical factors (local depth of the soil, ground cover type on the soil, size and shape of the grass tufts) upon soil macrofauna showed that all the factors significantly affected the richness and/or density of the soil macrofauna. In the study area, termite, earthworm and ant were the most abundant groups; the overall soil fauna was higher in covered soil (3 times) than bare soil.

A few studies indicate that landuse has no significant effect on the spatial distribution of soil invertebrate (Jiménez *et al.*, 2001), and studies (Rossi *et al.*, 1997) showed no direct relationship between soil abiotic factors and spatial distribution of soil fauna. Similar observation was also made by Mainoo *et al.* (2008). In both studies correlation between earthworm and soil organic matter could not be observed. Mainoo *et al.* (2008) showed a negative correlation between organic carbon and earthworm abundance, perhaps, the presence of earthworms depends on factors more important than organic carbon, and when present, organic carbon is consumed by earthworm.

2.7.1.1. Impact of agriculture on soil biodiversity

Soil is a fundamental resource base for agricultural systems besides being the main medium for plant growth. Soil functions to sustain crop productivity, maintain environmental quality and support animal and plant life as well. When forests are converted into agricultural land, either temporarily or permanently, there is drastic change in the soil biological and chemical properties of soil (Robertson *et al.*, 1993). In turn, a change in soil resource heterogeneity has huge potential effect on plant community structure and the distribution of soil living organisms (Tilman, 1988). In traditional agricultural systems, plots are cleared of their natural vegetation, then burnt and cropped for a few years only. Intensive agricultural systems often involve activities such as ploughing, drainage/irrigation, liming, use of pesticides and weedicides, which may increase the rate of mineralization and thus promote crop growth in short period, but speed up soil fertility depletion due to decline of soil organic matter content and affect soil fauna (Hairiah *et al.*, 2001).

It is generally accepted that soil biota are very responsive to human-induced disturbance (Swift and Bignell, 2001), but there is little data to support this. As intensification proceeds, aboveground biodiversity is reduced and the biological regulation of soil processes is altered and often substituted by the use of mechanical tillage, chemical fertilizers and pesticides (Hairiah *et al.*, 2001). But, the forest soil, which is relatively undisturbed, contains a large multitude of organic and mineral contents available as energy source, suitable for a vast array of animal and plant populations ranging from bacteria to fairly large, macroscopic organisms.

During the last decades, worldwide losses of biodiversity have occurred at an unprecedented scale and agricultural intensification, habitat fragmentations etc., are the major reasons for this (Perner and Malt, 2003; Fahrig, 2003). The landuse conversion is not a single phenomenon. Jha *et al.* (2000) reported that over the last 22 years (between 1973 and 1995) more than 25 per cent of forest cover was lost, dense forest decreased (19.5%) while degraded forests increased (26.64%). Consecutively, there was increase in the plantation and agricultural area and diversification and shifting of agriculture. It was reported that over the last few years there was drastic change in the landuse and cropping pattern (Mahesh, 1999; Kumar, 2005).

Intensified land use in agriculture and forestry is irrefutably the main cause of global change and biodiversity loss, though low-intensity landuse systems may have important role in biodiversity conservation. Agricultural land use affects large parts of terrestrial area, so its contribution to biodiversity is critical for successful conservation in the future (Tscharntke *et al.*, 2005), although this has not been acknowledged by most ecologists with their traditional emphasis on pristine ecosystems. Agricultural land holds much of the world's biodiversity (Pimental *et al.*, 1992), the relative contribution of each management type to conservation is little known. Biodiversity conservation will not work without protecting the just 5 per cent remaining pristine habitats, but also not without recognition of the contribution of the 'rest'. Agricultural land-use intensification may not only mean higher extinction, but also more resources enhancing populations, even of uncommon or endangered species. The often higher productivity of landuse, compared with natural systems, may provide more resources such as plant biomass and fruits (Tscharntke *et al.*, 2005). For this a landscape perspective is required to understand the negative and positive role of agricultural landscape on biodiversity conservation and other ecosystem functions.

2.7.2. Exotic plants and invasive species

Invasive species is of major concern to ecology and also have impact on soil biodiversity by alerting the biotic/abiotic environment. There is increasing evidence that exotic plants affect soil faunal community (Decaëns *et al.*, 2006; Mboukou-Kimbatsa *et al.*, 2007). It is reported that, exotic earthworms deeply modify the soil organic matter and water infiltration and soil chemistry (Burtelow *et al.*, 1998). Besides, peregrine earthworm, *P.corethrurus* causes severe compaction of soil (Chauvel *et al.*, 2000). Recent studies reported that invasion of exotic plants significantly reduced soil biota and also caused a species shift in plants, fungi and microarthropods (Belnap *et al.*, 2005).

2.7.3. Global change and soil fauna

Global climatic change is considered as one of the major threats to the Earth's biodiversity (Wardle *et al.*, 1998). Changes such as increased temperature, altered precipitation patterns and an increased frequency of extreme events (IPCC, 2007) are likely to affect many organisms (Shultz *et al.*, 2006).

It has been argued that the effects of global warming on soil biota will be maximum in the polar regions (Hodkinson *et al.*, 1998). Global change will probably also induce responses in the form of shifts in land-use that will have effects on the biodiversity

(Ramakrishnan *et al.*, 2005; O'rourke, 2006; Baldyga *et al.*, 2007). Though no direct effect of global change on soil fauna was noticed, this may occur through indirect change to the global vegetation and altered precipitation and increased temperature. This hypothesis is also supported by experimental manipulation of soil moisture, soil warming and increased soil fertilization to test the impact of global change on soil fauna (Lindberg, 2003). Besides, studies by Swift *et al.* (1998) demonstrated that temperature change, CO_2 enrichment and landuse change affect the composition as well as diversity of soil fauna in all the major terrestrial ecosystem of the world-tundra, temperate grassland and tropical rain forest.

2.8. Aboveground vs belowground biodiversity

There was mounting evidence that a complex suite of interactions exists between plants and both their associated 'above-ground' organisms (herbivores, pollinators, parasites and disease agents), and 'below-ground' organisms (soil biota such as decomposers, soil engineers, root herbivores and root disease agents) (Wardle, 2002; Scheu, 2003; Wardle *et al.*, 2004; de Deyn and van der Putten, 2005; Poveda *et al.*, 2005; Bezemer and van Dam, 2005).

Lavelle *et al.* (1997) proposed a pivotal functional role on the interactions between plant and belowground organisms. A strong linkage between above and belowground diversity may be expected, primarily because plants and plant diversity determine the functioning of the belowground ecosystem by regulating factors such as, plant litter quality, quantity and timing, the soil water balance and microclimate in the surface layer, and root at rhizosphere (van Noordwijk and Swift, 1999). Soil invertebrates, in turn, catalyze microbial exoenzymatic nutrient mobilization and increase the rate of plant growth, both by grazing upon bacteria and fungi and by continual predation upon grazer populations (Moldenke *et al.*, 1994).

2.8.1. Correlation between above and belowground diversity

Number of species above ground and below ground may be correlated when taxa in both habitats respond similarly to the same or correlated environmental driving variables, in particular across large gradients of disturbance, climate, soil conditions, or geographic area (Coleman and Whitman, 2005). Study by Sileshi and Mafongoya (2007) showed that the quantity and quality of biomass produced by the legume species had impact on the abundance of macrofaunal communities. The spatial heterogeneity in organic resource quality and quantity apparently explained most of the observed variation in the abundance of earthworms, beetles and millipedes, and they conclude that both quantity and quality of organic inputs have important role in the maintenance of diverse soil macrofauna. On the contrary, there was a negative or inverse relation between earthworm and termites density in different landuse systems (regional scale) because termites adapt habitat with poor quality or small amount of organic matter with low availability of water (Decaëns *et al.*, 1994). Difference in the scale of observation, interaction among species, resource heterogeneity etc. are the probable reasons for negative correlation (Hooper *et al.*, 2000).

There were contrary observations on the aboveground-belowground relation. Studies show that woodland species do not encourage soil fauna community that decomposes their litter (Ayres *et al.*, 2006). It is also interesting to note that (Dewenter *et al.*, 2007) transformation of near-primary forest to agroforestry had little effect on total species richness, though there was a considerable reduction in the plant biomass (=70%) and forest-using species (=60%).

2.8.2. Aboveground-belowground feedback

Differentiating between simple correlation and causation is often problematic, high diversity in plant species can result in high diversity of litter quality or types of litter entering the belowground system. This resource heterogeneity can lead to a greater diversity of decomposers and detritivores (Hooper *et al.*, 2000). In contrast, a high diversity of resources and species in soil could feed back to a high diversity aboveground, where certain species or functional groups are closely linked to groups belowground. Plant diversity can lead to a wider array and/or a more continuous supply of substrate for belowground system. In turn, the belowground biodiversity provide a number of environmental services to the plants (van Noordwijk *et al.*, 2004) and the functional relationship between aboveground and belowground biodiversity is mediated by roots.

It is also evident that soil fauna determine the magnitude and direction of litter diversity. Litter and soil fauna interactively determine the rate of litter decomposition (Hättenschwiler and Gasser, 2005) and understory vegetation also support more invertebrate fauna especially earthworms than other area. Studies showed that soil fauna influence plant (Setala and Huhta, 1991) and enhanced shoot biomass (Laossi *et al.*, 2008). Blouin *et al.* (2005) reported the positive effect of earthworm on rice (*Oryza sativa*) growth.

The forest is a high diverse system with small fluctuation in population abundance, steady nutrient cycling and regarded as relatively stable system. But agroecosystems does not have such feedback activities and are susceptible to adverse climatic or other anthropogenic activities (van Noordwijk *et al.*, 2004). The diversity itself is not leading to stabilization, but stable environment is required for the diversity to develop, and it is thought that belowground complexity and food-chain length increase with developmental (successional) age. Increase and decrease in the abundance of individual species depending on the probability of decolonization, which in turn depends on the accessibility and dispersal means of the species (van Noordwijk *et al.*, 2004).

2.9. Soil invertebrates as indicator species

Invertebrates in general are regarded as potentially powerful monitoring tools in environmental management (Paoletti *et al.*, 1991). They are relatively easy to sample, respond to a range of environmental stresses and may act as surrogate measures for nutrient cycling, changes in soil structural qualities and the overall connectivity of the soil food web. An obvious reason for examining soil macroinvertebrates as bioindicators relates to soil sustainability in agroecosystems.

As a general rule, large populations of earthworms are regarded as an indicator of soil "health". Earthworms are often large in size and hence constitute a noticeable component of soil fauna. They are diverse in their behavior and hence the niches they occupy. They respond to land management practices and their populations and biomass are frequently correlated with edaphic variables (Römbke *et al.*, 2005).

Among insects, Brown (1991) identified termites as potentially one of the most important indicator taxa. Evidences suggest that termites may prove useful and versatile as ecological indicators (Jones and Eggleton, 2000). Muller *et al.* (1997) also proposed the use of termites as an indicator taxon for ecosystem processes across a network of sites designed for monitoring the impact of land-use changes. Termites have the potential to act as indicators for decomposition processes in tropical rainforests and are sensitive indicator of habitat disturbances (Jones and Eggleton, 2000; Gillison *et al.*, 2003).

Despite variability among species, ant communities are highly sensitive to disturbance. This is exemplified by the use of ants for assessing restoration success at mining sites (Majer, 1983; Hoffman and Andersen, 2003) and in degraded sites (Andersen, 1993). Functional groups as well as species have been reported to perform in discriminating land condition (Andersen, 1995) and use of groups of species simplify the taxonomic limitation that potentially makes wide use of particular ants as indicator species difficult.

2.10. Economic aspects of soil biodiversity

Ecological economics is not a new field in ecology or economics; economic evaluation of ecosystem goods and service provided by soil fauna is seldom performed. Recently, economic valuation of these services has created interest among scientists (Huguenin *et al.*, 2006), who suggested that, degradation of soil fauna indicate a 'market failure'. For example, increased pesticide usage which has negative impact on soil fauna also lead to undesirable changes in the cropping system. These changes have negative economic impact.

Soil fauna have intrinsic as well as instrumental value (Decaëns *et al.*, 2006). The instrumental value refers to the potential use of a species by human beings. Based on this, soil fauna have both direct and indirect uses. Consumptive value is the main direct economic value of the soil fauna, while aesthetic value, scientific and educational value, recreational value, value of ecosystem goods and service by soil fauna are the important indirect economic value. But rating of many of these aspects is often problematic.

2.11. Conservation needs of soil biodiversity

Soil invertebrates are normally outside the immediate concern of conservationists. The Red Data Book lists 1891 (http://www.iucnredlist.org/; Daniel *et al.*, 1998) invertebrates as threatened, of which 193 are from India. Recently, Daniel *et al.* (1998) assessed the status of 94 soil invertebrate fauna, and reported that 64 per cent of fauna are categorized as threatened. This may be rather exaggerated, because most of the species mentioned were rarely distributed, low in population and taxa reported from a single location with few or no record after their initial studies were considered. Though, the situation seems alarming and needs further attention, at least some of the taxa may face extinction in course of time!

Reasons for species to be threatened may be due to habitat loss (35.6%), human interference (21.8%), followed by pollution (17.3%) and pesticide use (10.9 %). Studies show that (Woodman *et al.*, 2008) habitat destruction adversely affecting survival of major soil faunal components like earthworms, ants and termites. Habitat fragmentation, climate change, invasive animals and plants and fire are other important factors.

Chapter 3

GENERAL DESCRIPTION OF THE STUDY AREA

CHAPTER 3: General Description of the Study Area

3.1. The Nilgiri Biosphere Reserve (NBR)

The Nilgiri Biosphere Reserve is an International Biosphere Reserve in the Western Ghats. There are over 3,000 endemic plants in the fragmented forests of the Western Ghats. However, less than 15 per cent of the Western Ghats is protected as national parks and other areas set aside for conservation. The pressure on natural resources is immense. Recognizing that the Western Ghats is a global biodiversity hotspot, Nilgiri Biosphere Reserve (NBR) was constituted on 1st September 1986 under UNESCO's Man and Biosphere Programme. The Biosphere Reserve covering an area of 5520.40 km^2 encompasses the three States of Karnataka, Tamil Nadu and Kerala. The Reserve is located in the South Western portion of the Western Ghats, North of Palghat gap between 10^{0}45' to 12^{0}15' North latitudes and 76^0 15' and East longitudes (Fig. 3.1). Nilgiri Sub-Cluster, conjoining the Nilgiri Biosphere Reserve, is under consideration by the UNESCO World Heritage Committee for declaring as a World Heritage Site (UNESCO, 2007).

3.1.1. Kerala part of Nilgiri Biosphere Reserve

The Biosphere Reserve has an adequate area to serve major functions *i.e.,* conservation, development and logistic support. Kerala part of the reserve has a core zone area of 264.50 km^2, forestry zone of 915 km^2 and restoration zone of 245.90 km^2. The planned economic development initiated in 1950's together with adoption of forest policies focusing raw material demands of wood-based industries led to massive conversion of natural mixed forests to monoculture tree plantations. Implementation of land reforms initiated during 1960's led to large scale shifts in land use, both agricultural and forest lands. For example, in 1971, the Kerala Government passed the Private Forest (Vesting and Assignment) Act 1971, empowered it to take over thousands of square kilometers of private forests. The present landscapes in the Biosphere Reserve are mosaics consisting of natural forests with various degrees of disturbances, forest plantations, traditional farming systems and extensive mono-cultural crop lands.

The Kerala part of NBR falls in revenue districts of Kozhikode, Wayanad, Malappuram and Palakkad, and lies between 10^{0}45' and 12^0 15' North latitudes and between 76^{0}00' and 77^0 15' East longitudes (Fig. 3.1). NBR has highly varied physiographical characteristics ranging from Montane Ghats to the upland plateau of lower elevation. The

Western Ghats and Eastern Ghats meet at a point within NBR, the second highest peak in Southern India, Dodabetta (2670 m above sea level), situated in these ranges.

The Nilgiri plateau with an elevation of about (2000-2500 m) abruptly rises from the Coimbatore plains and slopes down to the North-West, gradually merging with the lower Wayanad plateau or Gudalur-Devala-Pandalur area. It slopes less gently to east and south-east. The Attapadi Valley is an extensive secondary plateau merging imperceptibly with Muthikulam Reserve Forest located near Palakkad gap. From the western edge of Nilambur plateau, extend a number of steep parallel edges, running 10-12 km to the west and merging with the Nilambur plains having a mean elevation of less than 300m in between the parallel edges, the Nilgiri descends precipitously to the west forming the abrupt ending valley. The entire western phase of Nilgiri is drained by Chaliyar river system, while the eastern side constituting the high land plains having mean elevation of 800 m is drained by the greater Cauvery river system. Bhavani, Kabini, Moyar Noyil, Suvarnavati, all these form the sub-basins of the greater Cauvery river basin.

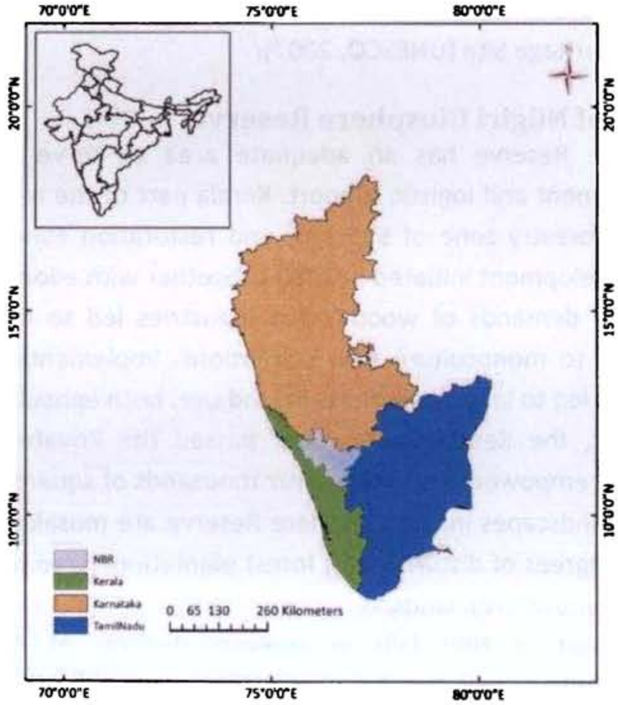


Fig. 3.1. The Nilgiri Biosphere Reserve (Base map source: Geomatic lab, KFRI)

3.2. Chaliyar watershed

The Chaliyar watershed lies between $11^{0}05'$ to $11^{0}40'$ North latitude and $75^{0}35'$ to $76^{0}45'$ East longitudes and is located in the Kozhikode, Malappuram and Wayanad Districts of Kerala (Fig. 3.2). The watershed has total area of 2539.82 km^2; covering 63 villages spread over 55 Panchayats, 10 blocks and 3 districts (KSLUB, 1995). The Chaliyar watershed is divided into 80-sub-watersheds and 382 micro-watersheds (KSLUB, 1995).

The Chaliyar River, also known as Beypore River, emerges from Elambaleri hills of Wayanad at an elevation of 2068 m above msl and flows to Arabian Sea. The general elevation ranges from 2594 to 78m in the upper region, 74 to 9m in the middle region and less than 5m in the lower region (KSLUB, 1995). The Chaliyar River emerges from northern part and flows westwards to join the Arabian Sea near Beypore.

The Karakkode River is a micro-watershed of river Chaliyar, which irrigates most part of the area. The different cropping systems of the study area are presented in Fig. 3.3.

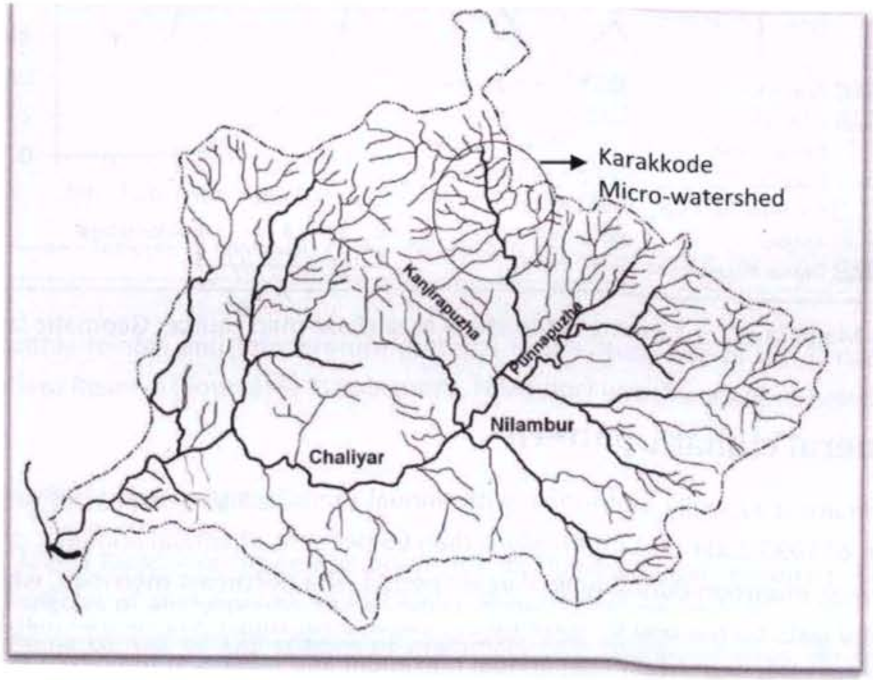


Fig. 3.2. Watershed map of Chaliyar (Base map source: Geomatic lab, KFRI)

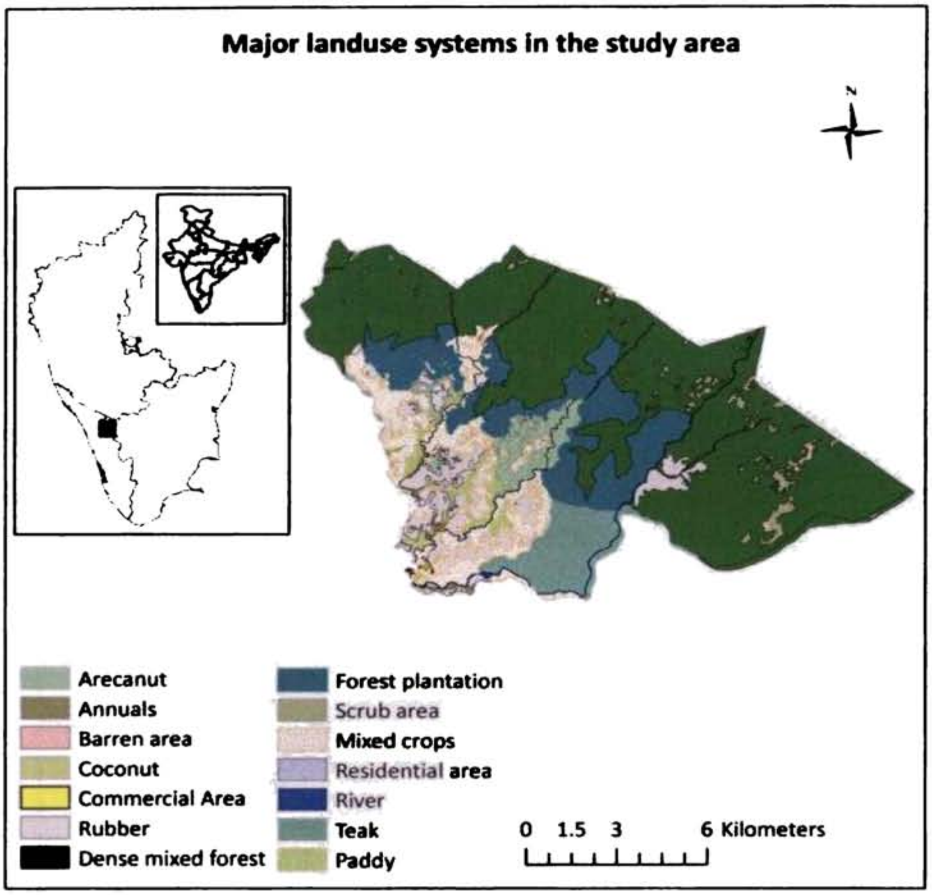


Fig. 3.3. Major landuse systems in the study area (Base map source: Geomatic lab, KFRI)

3.3. General climatic pattern

The climate is typically monsoonic with annual rainfall varying from 1621mm to 3271 mm (mean of 1990-2004- 2312mm). More than 65 per cent of annual rainfall is drawn from the southwest monsoon during June- August period. The northeast monsoon, which sets in October and lasts till the end of November, accounts for much less rainfall (hardly 25% of annual rainfall) (Fig. 3.4). The mean annual maximum and minimum temperatures are 35^0C and 15^0C, respectively. Relative humidity does not show drastic changes (Table 3.1).

Table 3.1. Monthly mean values of relative humidity (% recorded at 8-30 hrs. and 17-30 hrs. representing the southern part of the watershed) (Source: Automatic weather station, KFRI Subcentre, Nilambur)

Time	J	F	M	A	M	J	J	A	S	O	N	D
08.30	71	75	75	76	76	91	92	90	81	85	76	64
17.30	57	61	61	69	69	86	92	81	74	80	70	56

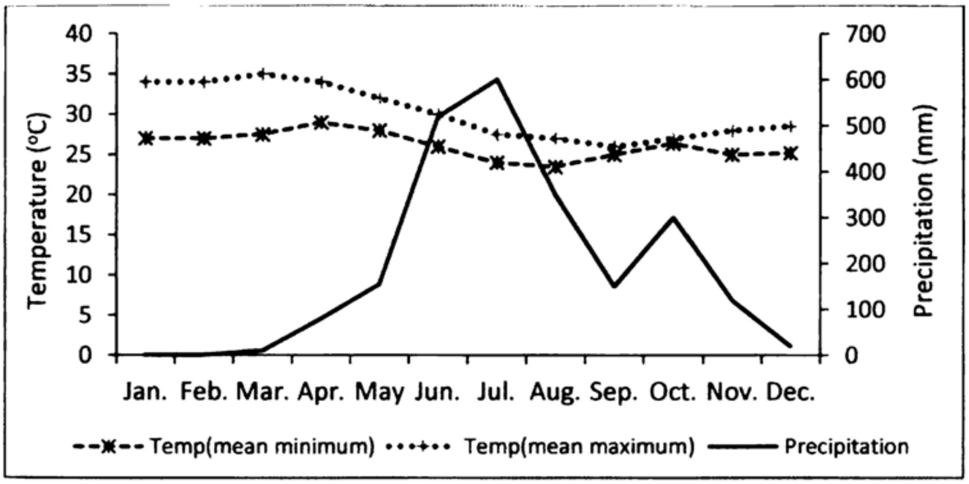


Fig. 3.4. Monthly rainfall and temperature patterns in the study site in the Kerala part of Nilgiri Biosphere Reserve (Source: KFRI Subcentre, Nilambur) weather station record

3.4. Biological Resources

The Nilgiri Biosphere Reserve is noted for its rich biological resources. There are about 3,500 species of angiosperms, out of which about 1,500 are endemic to the Western Ghats. The fauna consist of 139 species of mammals, 508 species of birds, 80 species of reptiles, 179 species of amphibians, 120 species of fishes and an unknown number of invertebrates (http://wwf.panda.org/what_we_do/where_we_work/western_ghats/; http://en.wikipedia.org/wiki/Western_Ghats).

3.5. Landuse history

The Kerala part of NBR consists of Silent Valley, having virgin forest ecosystems devoid of any landuse practices. The adjoining regions such as Mannarkkad and Nilambur have vested forests and have been heavily exploited by erstwhile owners. In Nilambur and Wayanad most of the virgin forests were clear felled and converted into teak plantations to meet the local demands. During the post-independence period, the emphasis on economic growth further accelerated clearing of forests and expansion of plantations.

The Nilambur region of Biosphere Reserve was part of old Malabar and considered to be a private property. British rulers formally took possession of the forests, though no steps were taken to exercise right of their possession. Malabar areas were the source of timber for Bombay Naval Dockyard even before 1840. Plantation activity commenced from 1850-53 on forest land taken on lease, gap filling by teak and *Hopea* in 1850s.

The present study was conducted in the watershed area of Karakkode rivulet, one of the tributaries of Chaliyar River (Fig. 3.2). The watershed can be divided into fertile, relatively flat valley along the rivulet and surrounding uplands with medium to steep slopes. Valley area around the rivulet is by and large under agriculture. Forests are mainly confined to higher slopes and consist of both natural forests and teak and bamboo plantations. Rural people, with different social and economic conditions in the area primarily depend on agriculture for their livelihood.

3.5.1. Changes in crop pattern

The cropping pattern in the Kerala State is quite different from elsewhere in the country owing to its topography and climatic conditions. Perennial crops dominate the cultivated area in the State. Over the years, extend of perennial crops has been gradually increasing.

The area under rice has nearly halved during the past two decades. The area under tapioca, which is a cereal substitute, has also considerably declined, to about one-third. The area under vegetables has gone down by nearly two-thirds. Among the crops that have expanded in areas under cultivation, the most significant is rubber which has more than doubled its area, followed by coconut and pepper which have increased their area by nearly one-third and three-fourth respectively. Thus, it will be seen that in the process of inter-crop adjustments, food crops, in general are the losers and perennial cash crops, the gainers. The trend that has been persisting for the last two decades is still continuing (Chandrashekara *et al.*, 2008).

Except for rice and plantation crops, most of the other crops are raised under a multi-tier cropping system in and around the homesteads. In most of the homesteads coconut is the base crop and other crops like pepper, banana, arecanut, tapioca, and tubers are grown as inter crops. Thus one acre coconut garden may contain, in addition to the coconut palms, tubers, banana, pepper, ginger, turmeric, etc. This mixed cropping system is destroyed when the land is used for rubber cultivation, since no other crops grow under rubber trees. Earlier, rubber was grown only in the valleys and other areas where miscellaneous tree crops were grown. Most of the land is recently converted to cultivation of rubber.

3.5.2. Changing pattern in the study area

After independence, the State witnessed dramatic landuse changes. Most of these changes took place in the migratory places nearby high range valleys, where plenty of fertile land was available. People from rest of the State were migrated to these areas and cleared much of the virgin land for cultivation. The landuse changing history and local migration of people starts here (http://en.wikipedia.org/wiki/Malabarmigration). Huge tracts of virgin forests were converted at this time and main crop under cultivation was paddy because it is the staple food of Kerala. As time passed, due to various socio-economic and political reasons (Kumar, 2005), land was slowly converted extensively for planting other cash crops. Most of the conversion started with the shifting of the area to cultivation of vegetables, banana, and tapioca; a portion of the land converted thus is later used for growing perennial cash crops like coconut, arecanut, and pepper (appendix Chart A1). Some of the converted areas were subsequently used for construction of houses and roads and also later transformed into non-agricultural land (Chandrashekara *et al.*, 2008).

Chapter 4

METHODS

CHAPTER 4: Methods

4.1. Site selection

The experimental area is located at Vazhikkadavu near Nilambur of Malappuram District (see Fig. 3.2). Within this area, detailed study was conducted in the Karakkode micro-watershed (between $11^{0}15'$N and $11^{0}\ 27'$N; between $76^{0}17'$E and $76^{0}24'$E) of Chaliyar River in the Kerala part of Nilgiri Biosphere Reserve. The area was divided into 200 m x 200 m grids and the intersection point of grids were marked using a Geographical Positioning System (GPS).

Most of the landuse systems were derived from the forest ecosystems (Chandrashekara and Baiju, 2005). As population pressure increased, large areas of virgin forests were cleared for cultivation mainly for annuals like paddy, vegetables and perennial crops such as banana (Table 4.1). Later, rice production became uneconomical, most of the farmers gradually switched-over to cultivation of other cash crops and monoculture plantations of arecanut (*Areca catechu* L.), coconut (*Cocos nucifera* L.), rubber (*Hevea brasiliensis* L.), cashew (*Anacardium occidentale* L.) and teak (*Tectona grandis* L.). Paddy is still being cultivated in some areas. The agricultural management practices involve bush burning during land clearing, applying fertilizer, lime, herbicides and insecticide, and irrigation.

In total, 15 different land-use systems could be recognized at the above site based on specific practices (Table 4.1, Plates I-IV). These fell under four main ecosystems, based on the biophysical conditions and management practices. They were agricultural ecosystems, agroforestry systems, plantations and forest ecosystems. The agricultural systems consisted of mainly annual crop fields (PA). Agroforestry practices consisted of homegardens (HG), polyculture farms (OG), arecanut with annuals (AV), arecanut with perennials (AM) and coconut with perennials (CM). Plantations consisted of monoculture stands of arecanut (AR), coconut (CO), rubber (RU), cashew (CA), teak plantations managed by the Forest Department (TE-KFD) and teak plantations managed by private land owners (TE). The forest ecosystem consisted of degraded forest (DF) moist deciduous forest (MDF) and semi-evergreen forests (SEF).

4.2. Faunal sampling

4.2.1. Soil monoliths

For the sampling of soil fauna, protocols suggested by Tropical Soil Biology and Fertility programme (TSBF) were followed (Swift and Bignell, 2001). Soil monoliths (25cm x 25cm x 30cm) were removed by digging out the soil. Sampling was done in the 15 landuse systems within the four main ecosystems described above. In each landuse type, four spatially different plots were taken. From each plot four soil monoliths were taken randomly, making a total of 16 samples for each landuse type. Soil was placed over polythene sheet and soil macrofauna were hand sorted and preserved in alcohol (Plate V).

Initially, soil fauna was grouped to higher taxonomic levels (*i.e.,* supra-specific taxa including families and above) and detailed taxonomic and community composition study were attempted for three major groups of soil invertebrates (**Ant, Earthworm and Termite**). For the remaining groups, only higher taxonomic order was considered. The practice of sampling higher taxonomic levels or species surrogacy (Oliver and Beattie, 1996; Ward and Larivière, 2004) has recently received substantial attention in rapid biodiversity assessment and environmental monitoring (Duelli and Obrist, 2003; Ward and Larivière, 2004). This is because surveys can either cover large areas or a large taxonomic spectrum but both together would be impossible, since the efforts for the identification of the numerous species would be prohibitive (Duelli and Obrist, 2003). In such a situation, it is more efficient to resort to sampling supra-specific taxa or morphospecies (Krell, 2004; Oliver and Beattie, 1996), which are groups of organisms that belong to at least the same taxonomic class and order, and those look very similar. The advantage of higher taxa in surveys is that costs could be substantially reduced as the time-consuming task of identifying specimens to species level becomes unnecessary (Duelli and Obrist, 2003; Oliver and Beattie 1996; Ward and Larivière, 2004).

Parataxonomic sorting of samples to recognizable taxonomic units (parataxonomic units) is generally considered to be a sufficiently reliable and conservative approach in ecological biodiversity studies or conservation biology (Krell, 2004). For indepth study, three parataxonomic units (Ants, Earthworms and Termites) alone were considered, and their diversity, functional group characterization and spatial distribution were studied. Field study was carried out during 2004-2005, and sampling was conducted for two seasons, pre-monsoon (during April-May) and post-monsoon (during September-October).

Table 4.1. Land-use systems and their features in the study area

Ecosystem	Landuse type	Description
Natural forests	Semi-evergreen forest (SEF)	Comprises a mixture of evergreen and deciduous trees. Between 40% and 80% trees are evergreen.
	Moist deciduous forest (MDF)	Deciduous trees are dominant. Up to 40% trees are evergreen.
	Degraded forest (DF)	Deciduous trees are dominant, trees sparsely distributed. Tree regeneration is poor.
Plantation	Teak plantations (TE-KFD)	Monoculture plantations of teak (*Tectona grandis* L.) managed by the Kerala Forest Department
	Areca nut plantation (AR)	Monoculture plantations of Betel or areca nut (*Areca catechu* L.)
	Coconut plantation (CO)	Monoculture plantation of coconut (*Cocos nucifera* L.)
	Rubber plantation (RU)	Monoculture plantation of rubber (*Hevea brasiliensis* L.)
	Cashew plantation (CA)	Monoculture plantation of cashew (*Anacardium occidentale* L.)
	Teak plantation (TE)	Monoculture plantation of teak (*Tectona grandis* L.) managed by private land owners
Annual crop systems	Annual crops (PA)	Annuals like paddy and vegetables dominant and perennials like banana constitute minor crops
Agroforestry	Homegardens (HG)	Land cultivated around the farmer's dwelling place with annual, biennial and tree crops, mostly integrated with animal husbandry.
	Polyculture farmlands (OG)	Land cultivated away from the farmer's dwelling place with annual, biennial and tree crops.
	Areca nut with annual crops (AV)	Areca nut plantation integrated with annual crops such as paddy (rice) and vegetables.
	Areca nut with perennial (AM)	Areca nut plantation integrated with perennial crops such as bananas.
	Coconut with perennial (CM)	Coconut plantation integrated with perennial crops like bananas

4.2.2. Pit fall trapping

Total of 8 pit fall traps were placed in each landuse type studied. Each has 10cm mouth diameter and 15cm depth. The traps were placed in such a way that the rim of the bottle not projecting out of the ground surface. Water was added to the bottle along with bit of detergent in order to reduce surface tension, which prevent escape of organisms from the trap (Plate VI).

4.2.3. Line transect for termite sampling

In addition to the hand sorting method to collect termites, one time line transect sampling method was also employed for termites. Transect was 40 m long and 2.5 m wide, and divided into 10 contiguous sections (each 4 m x 2.5 m in area). Each section was sampled for one hour. Within each section, the following microhabitats were searched-surface soil up to 10 cm depth, dead logs, dead branches and twigs; mud plaster on dead logs and tree stumps. All castes of termites were collected if present, and care was taken to collect the soldier caste, as they are required for identification. The collected termites were kept in vials containing 80 per cent alcohol and labeled with the section number (Plate VI).

The transect protocol provides a measure of the relative abundance of termites based on the number of encounters with each species in a transect. The protocol is being accepted and followed widely in the tropical forest ecosystems (Jones and Eggleton, 2000). The sampling protocol is particularly advantageous as the sampling effort and area are standardized. Thus a more meaningful and accurate comparison becomes possible among the land use systems in terms of termite diversity.

4.3. Study of environmental parameters

4.3.1. Climatic factors

Monthly average of rainfall data and month-wise mean value of humidity was gathered from automatic weather station, KFRI Subcentre, Nilambur. Mean variation in rainfall over a period of ten years was considered in the current study.

4.3.2. Physico-chemical aspects of soil

Soil was analyzed for physico-chemical parameters. Soil moisture content, bulk density, texture and soil chemical parameters like pH, Nitrogen (N), Phosphorous (P), Potassium (K), Calcium (Ca), Magnesium (Mg) and Organic Carbon (OC). Soil profile of representative landuse systems was also studied, which gave an insight into the soil characteristic of each system. Sand, silt, clay contents were also studied. Information on vegetation parameters like tree, herb and shrub density was collected. How it was coll

4.3.3. Assessment of management characteristics

For each landuse type, especially agricultural systems in the study area, management characteristics were assessed. The management was characterized with respect to management intensity, spatial arrangements and use of management inputs. The assessment of the management intensity was based on a detailed assessment of the management practices for the agricultural systems. The management intensity was characterized according to the technique of Wiersum and Singerland (1998). The intensity of management is a crucial information for soil invertebrates, and information on fertilizer input and pesticide usage was collected.

4.4. Data analyses

The data collected were analyzed using the statistical software packages of SAS 9.1 (SAS Institute Inc.) and R project 2.8.1 (R Development Core Team, 2008) using packages: Vegan (Oksanen *et al.*, 2008), ade4 (Dray and Dufour, 2007; Chessel *et al.*, 2004; Dray *et al.*, 2007; ADE4 standalone (Thioulouse *et al.*, 2001); ade4TkGUI (Thioulouse and Dray, 2008).

For the count data, descriptive statistics like mean and standard deviation was calculated in order to interpret the abundance. The data are expressed as (1) diversity of ecosystem engineers *i.e.*, ant, earthworm and termite from each landuse type sampled, (2) abundance of all macrofauna (individuals/m^2), (3) total count of individuals of all taxa per monolith.

All counts were analysed using generalized linear models (GLMs). This method was chosen because the counts for each taxon were over-dispersed. If not properly modelled, over-dispersion can lead to underestimation of the standard errors of regression parameters, confidence intervals that are too narrow, and P-values that are too small. This can result in biased estimation of ecological effects and jeopardize the integrity of the scientific inferences (Sileshi, 2008). Model choice can have a striking effect on the standard errors of parameter estimates and the 95 per cent confidence intervals (Sileshi, 2008).

GLMs assuming the negative binomial distribution, zero-inflated Poisson or zero-inflated negative binomial distribution were used as deemed appropriate for the data using information theory (Sileshi, 2008). These models were chosen because they allow for the non-normality and over-dispersion common in soil invertebrate counts (Sileshi, 2008). Zero-inflation, a special case of over-dispersion, creates problems for sound statistical inference by violating basic assumptions implicit in standard distributions. The best count distribution model for each animal count data was selected by comparing Akaike's information criterion (AIC) values. This has been shown to be a more appropriate approach for comparing models than the traditional likelihood ratio statistic (Johnson and Omland, 2004; Sileshi, 2008). Regression model is written as follows: Count = m + LU + B + LU*B + e, where m is the intercept, LU is the fixed effect of land use type, B is the blocking factor (replicate), LU*B is the interaction between LU and blocking and e is the error (monolith).

The data consisted of an array of values corresponding to p variables (*i.e.*, the macrofauna groups) recorded for n sites at t replicates, leading to a data table with *p* columns (variables) and *nt* rows (objects). The data were analyzed using a principal components analysis (PCA). Single-linkage cluster analysis based on the normalised minimum distance was conducted to classify land-use practices into homogeneous subsets. The pseudo F, pseudo T^2 and the cubic clustering criterion (CCC) were used to determine the optimum number of clusters.

A multivariate direct gradient analysis (Canonical Correspondence Analysis-CCA) was conducted to interpret the abundance of soil fauna. In CCA ordination method, ordination axes are chosen in the light of environmental variables and the soil fauna community variation can be directly related to environmental variation, by a linear combination of environmental variation (ter Braak, 1986), and it looks for an estimate of multiple regression of the sample scores of the environmental variables. CCA assumes that species have a Gaussian (Bell-Shaped) distribution along the complex environmental gradients. In CCA, correlation is maximized instead of covariance.

Principal component analysis (PCA) is one of the oldest ordination techniques. It provides graphs that show the Euclidean distance between sites. The total variance is the total variance of the species between sites. It is the sum of the individual variances of each species (species are arranged in column) of the species matrix. Since PCA is an unconstrained ordination method, the unconstrained variance equals the total variance. PCA is a technique that creates new axes (or a matrix with new columns). The distances between the sites will remain the same in the new matrix (and thus the total variance remains the same). The advantage of the creation of new principal component axes is that more variance will be shown for the first two new axes, than if we plotted two original species axis. We can thus see a larger fraction of the total distance between sites. The species scores show the direction from the origin (the point with coordinates (0,0) shown in the middle, where sites occur that have a larger than average value for the particular species. While examining correlation among species, species that have a small angle between their vectors are expected to be strongly positively correlated. Species with angles between vectors at 90 or 270 degrees are expected not to be correlated and species with angles of 180 degrees are expected to be strongly negatively correlated.

Interpretation of CCA ordination plot is same as PCA. Canonical correspondence analysis is a multivariate direct gradient analysis technique, whereby a set of species is related directly to a set of environmental variables. The technique identifies an environmental basis for community ordination by detecting the patterns of variation in community composition that can be explained best by the environmental variables. In the resulting ordination diagram, species and sites are represented by points and environmental variables are represented by arrows. Such a diagram shows the main pattern of variation in community composition as accounted for by the environmental variables, and also shows, in an approximate way, the distributions of the species along each environmental variable. The technique thus combines aspects of regular ordination with aspects of direct gradient analysis. The solution of canonical correspondence analysis can be displayed in an ordination diagram with sites and species represented by points, and environmental variables represented by arrows. The species and site points jointly represent the dominant patterns in community composition insofar as these can be explained by the environmental variables, and the species points and the arrows of the environmental variables jointly reflect the species' distributions along each of the environmental variables.

Chapter 5

RESULTS

Chapter 5.1

Diversity of ecosystem engineers

CHAPTER 5.1: Results

5.1. Diversity of ecosystems engineers

5.1.1. Ant diversity and community structure

Out of the three groups studied, ant (Hymenoptera: Formicidae) was the most diverse group in the study area. A total of 27 species under 17 genera and 5 subfamilies (Table 5.1.1, Plate VII) were collected. Of the five subfamilies reported, Myrmicinae was the most diverse with 8 genera and 12 species; subfamily Formicinae with 8 species in 3 genera. Five species were collected under the subfamily Ponerinae, but under Dolichoderinae and Ectatomminae subfamily, only one species each was collected. *Camponotus* was the most diverse genera with six species, followed by *Monomorium* with three species.

5.1.1.1. Abundance of ants in different landuse systems

Ants were collected from all landuse systems and from all plots, but showed a non-uniform distribution (Fig. 5.1.1). Highest numerical abundance (248 individual m^{-2}) was observed in plot 8 in semievergreen forest (SEF) followed by plot 41 of homegarden (HG) (180 individual m^{-2}). Least abundance (4 individual m^{-2}) was observed in plot 31 of coconut (CO) and in plot 55, belonging to private teak plantation (TE). Abundance of ants also varied among the plots of a given landuse system. (Result based on statistical analysis is given in Chapter 5.2).

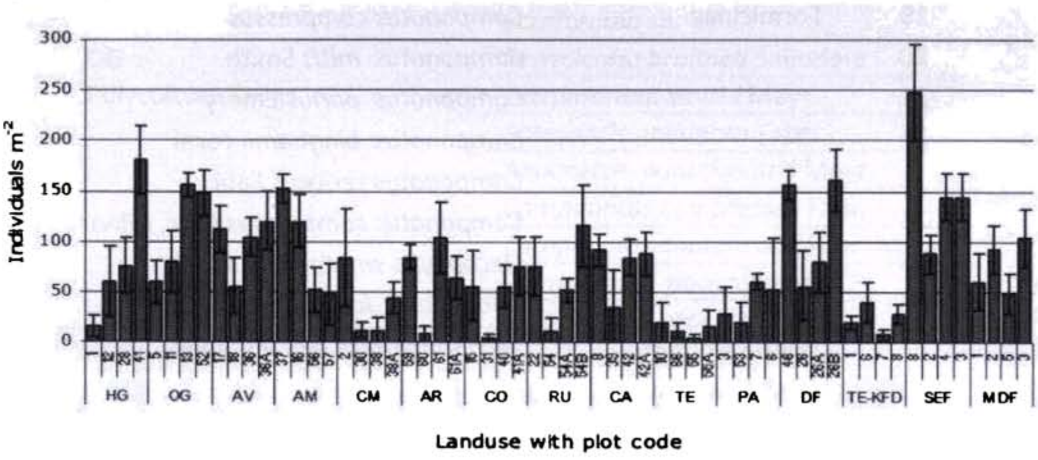


Fig. 5.1.1. Abundance (mean±SE) of ants (ind.m^{-2}) from plots of different landuse systems

Table 5.1.1. List of ants collected from different landuse systems

Sl. No	Family	Species
1	Myrmicinae	*Monomorium* sp.
2		*Monomorium floricola* Jerd
3		*Monomorium dichroum* Forel
4		*Meranoplus rothneyi* Forel
5		*Myrmicaria brunnea* Saunders
6		*Tertaponera rufonigra* (Jerd)
7		*Solenopsis geminata* Fabr.
8		*Cardiocondyla parvinoda* Forel
9		*Cardiocondyla wroughtoni* Forel
10		*Crematogaster rothneyi* Forel
11		*Tetramorium rothneyi* Forel
12		*Tetramorium smithi* Mayr
13	Ponerinae	*Lobopelta birmana* Forel
14		*Lobopelta ocellifera* Roger
15		*Anochetus punctiventris* Mayr
16		*Diacamma assamense* Forel
17		*Odontomachus punctulatus* Forel
18	Ectatomminae	*Ectatomma* sp.
19	Formicinae	*Camponotus compressus* Fabr.
20		*Camponotus mitis* Smith
21		*Camponotus parius* Emery
22		*Camponotus binghamii* Forel
23		*Camponotus sericeus* Fabr.
24		*Camponotus compressus* Fabr. Minor
25		*Oecophylla smaragdina* Fabr.
26		*Anoplolepis longipes* Jerdon
27	Dolichoderinae	*Technomyrmex albipes* Smith

5.1.1.2. Habitat-wise distribution of ant species

Of the four main ecosystems studied (Annual crops, Agroforestry, Plantation and Forests), annual crops showed least diversity of ants (Table 5.1.2,). Plantation, forest and agroforestry ecosystems came second, third and fourth position, respectively. While considering individual landuse systems, polyculture farms (OG) ranked first with 12 species followed by semievergreen forest (SEF) and homegarden (HG) with 7 species and moist deciduous forest (MDF) with 5 species.

Among the 27 species of ants collected, the foraging species *Myrmicaria brunnea* showed wide spread distribution and was recorded from all landuse systems. *Anoplolepis longipes* was the second common species present in six out of 15 landuse studied. Different species of *Camponotus* also showed wide spread distribution and is reported from 7 landuse systems (Table 5.1.2). Other species showed more or less a patchy distribution.

Table 5.1.2. Landuse-wise distribution of ants in the Kerala part of NBR

Code/Landuse system	**Species collected**
HG Homegarden	*Monomorium* sp. A
	Monomorium floricola Jerd
	Myrmicaria brunnea Saunders
	Camponotus compressus Fabr.
	Camponotus mitis Smith
	Anoplolepis longipes Jerdon
	Ectatomma sp.
OG Polyculture farms	*Myrmicaria brunnea* Saunders
	Tetramorium smithi Mayr
	Solenopsis geminata Fabr.
	Anochetus punctiventris Mayr
	Camponotus compressus Fabr.
	Camponotus compressus Fabr. Minor
	Camponotus parius Emery
	Camponotus sericeus Fabr.
	Anoplolepis longipes Jerdon
	Cardiocondyla wroughtoni Forel
	Technomyrmex albipes Smith
	Meranoplus rothneyi Forel

AV Areca with annuals	*Monomorium dichroum* Forel
	Myrmicaria brunnea Saunders
	Diacamma assamense Forel
	Camponotus parius Emery
AM Areca with perennials	*Myrmicaria brunnea* Saunders
	Camponotus binghamii Forel
	Oecophylla smaragdina Fabr.
	Odontomachus punctulatus Forel
CM Coconut with perennials	*Oecophylla smaragdina* Fabr.
	Myrmicaria brunnea Saunders
AR Areca	*Myrmicaria brunnea* Saunders
	Camponotus compressus Fabr.
CO Coconut	*Myrmicaria brunnea* Saunders
	Oecophylla smaragdina Fabr.
	Camponotus compressus Fabr.
RU Rubber	*Cardiocondyla parvinoda* Forel
	Crematogaster rothneyi Forel
	Tetramorium rothneyi Forel
	Myrmicaria brunnea Saunders
	Anoplolepis longipes Jerdon
CA Cashew	*Myrmicaria brunnea* Saunders
	Oecophylla smaragdina Fabr.
	Anoplolepis longipes Jerdon
TE Teak-private	*Myrmicaria brunnea* Saunders
	Oecophylla smaragdina Fabr.
PA Annual crops	*Tetramorium smithi* Mayr
	Myrmicaria brunnea Saunders
DF Degraded forest	*Tertaponera rufonigra* (Jerd)
	Lobopelta birmana Forel
	Myrmicaria brunnea Saunders
	Lobopelta ocellifera Roger
TE-KFD Teak plantation-KFD	*Myrmicaria brunnea* Saunders
	Camponotus compressus Fabr.
	Ectatomma sp.
SEF Semi evergreen forest	*Myrmicaria brunnea* Saunders
	Anoplolepis longipes Jerdon
	Diacamma assamense Forel
	Odontomachus punctulatus Forel

	Camponotus mitis Smith
	Monomorium sp. A
	Camponotus compressus Fabr.
MDF Moist Deciduous Forest	*Myrmicaria brunnea* Saunders
	Anoplolepis longipes Jerdon
	Oecophylla smaragdina Fabr.
	Odontomachus punctulatus Forel
	Crematogaster rothneyi Forel

5.1.2. Earthworm diversity and community structure

Earthworms (Annelida:Oligochaeta) showed patchy distribution in different landuse systems. Though they are important components of the soil ecosystem and coined as ecosystem engineers, their density and distribution was limited to certain habitats of the study area.

A total of seven species, under five families were recorded (Table 5.1.3, Plate VIII), among this *Pontoscolex corethrurus* (Glossoscolecidae) showed wide spread distribution.

Table 5.1.3. Earthworms collected from different landuse systems

Sl.No	Family	Species	Landuse systems
1	Acanthodrilidae	*Dichogaster affinis*	HG
2	Moniligastridae	*Drawida* sp. A	SEF, MDF, HG, OG, AR
3		*Drawida* sp. B	SEF, MDF
4	Almidae	*Glyphidrilus* sp.	CO
5	Megascolecidae	*Lampito mauritii*	PA, AR, CO
6		*Megascolex* sp.	MDF, SEF
7	Glossoscolecidae	*Pontoscolex corethrurus*	HG, OG, PA, RU, TE, TE-KFD, CO, CM, AR, AM, CA, AV, DF, SEF

5.1.2.1. Habitat-wise distribution and functional categorization

Maximum diversity of earthworms was recorded in semi-evergreen forests, with four species, followed by moist deciduous forest, with three species (Table 5.1.3). Landuse systems under forest ecosystems (SEF and MDF) shared common species. The peregrine species, *P. corethrurus* was the most abundant species in crop based systems and was also collected from SEF. *Megascolex* sp. and *Drawida* sp.B were recorded exclusively from forest ecosystems-both from semi-evergreen and moist deciduous forests, while *Glyphidrilus* sp., which is a semi-aquatic inhabitant, was recorded from the coconut based landuse systems.

Looking at the functional-ecological-categories of earthworms, the *Megascolex* sp. was the only epigeic species, which was recorded from forest ecosystems. *Drawida* sp. and *L. mauritii* are anecic species. Endogeic species, *P. corethrurus* was the abundant species, which accounted for >90 per cent of the total collection.

5.1.2.2. Abundance of earthworms in different landuse systems

The highest numerical abundance (639 individuals m^{-2}) and lowest numerical abundance (four individuals m^{-2}) was observed in coconut mixed with perennial systems (CM), in plot 2 and in plot 30 and 38A respectively, followed by plot 5 of moist deciduous forest (MDF) (456 individuals m^{-2}) (Fig. 5.1.2). (Result based on statistical analysis is given in Chapter 5.2).

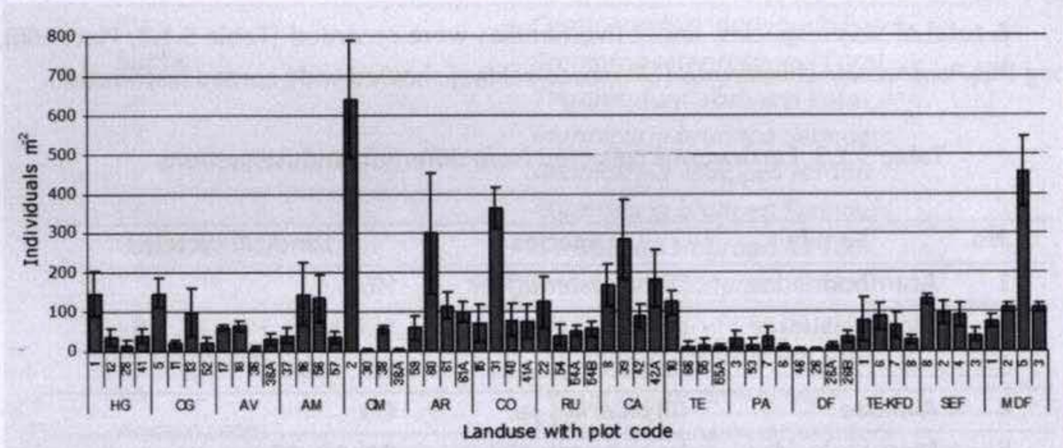


Fig. 5.1.2. Abundance (mean±SE) of earthworms (ind.m^{-2}) from plots of different landuse systems

Least abundance was recorded from certain plots of degraded forests and coconut mixed with perennials (CM). The data clearly show the difference in the abundance of earthworms amongst landuse systems.

5.1.3. Termite diversity and community structure

Termites (Isoptera) are the most important components of belowground biodiversity and they attain very high population density. In the present study, diversity of termites was confined to a very few species compared to ants. But their density was comparatively high in some habitats like natural forest.

A total of six species, under 5 genera and two families were collected (Table 5.1.4, Plate VIII) during the study. Among the five genera, *Odontotermes* with two species, and the others were with a single species each.

5.1.3.1. Habitat-wise distribution of termites

Forest ecosystems showed maximum diversity of termites with five species (Table 5.1.4). Plantation ecosystems had three species while agroforestry and annual crops had only one species each. Two landuse systems in the forest ecosystem (MDF and SEF) had four species each and shared three species while one species was collected exclusively from each landuse type. *O. obesus* showed wide distribution and spread all over the agroforestry systems.

Table 5.1.4. List of termites collected from different landuse systems

Sl. No.	Species	Family : Subfamily	Landuse systems
1	*Dicuspiditermes* sp.	Termitidae: Termitinae	TE , TE-KFD
2	*Labiocapritermes* sp.		MDF
3	*Odontotermes obesus*	Termitidae: Macrotemitinae	MDF, SEF, DF, TE-KFD, HG, OG, CM, AV, CO, RU, TE, PA, CA, AR, CM
4	*Odontotermes feae*		MDF, TE-KFD, SEF
5	*Trinervitermes* sp.	Termitidae: Nasutitermitinae	SEF
6	*Heterotermes* sp.	Rhinotermitidae: Heterotermitinae	MDF, SEF

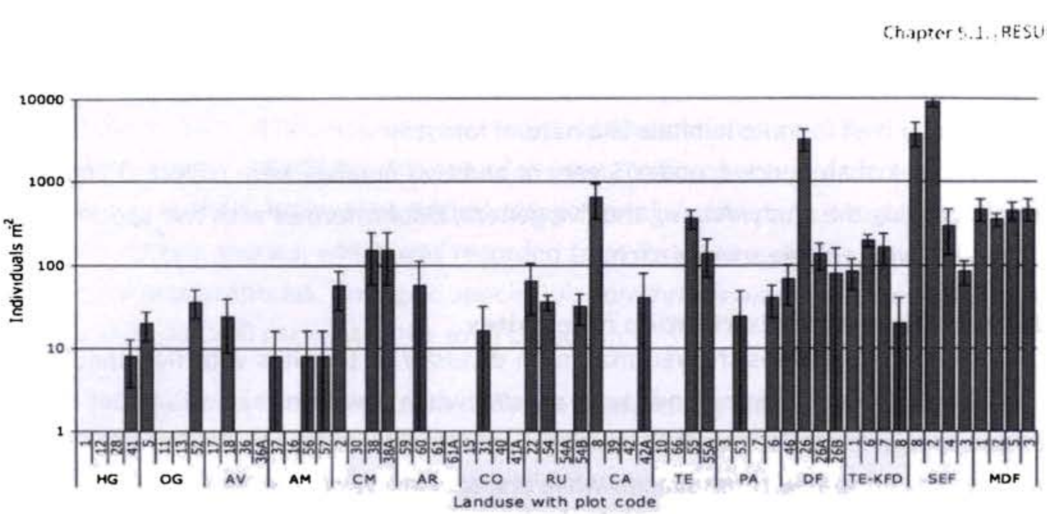


Fig. 5.1.3. Abundance (mean±SE) of termites (ind. m^{-2}) from plots of different landuse systems

5.1.3.2. Abundance of termites in different landuse systems

Termites were absent in many landuse types (Fig. 5.1.3). In most of the plots in the agroforestry systems, termite was not recorded. While comparing with agroforestry systems, individual plots as well as landuse types under plantation habitat showed more number of termites. This was the case with annual crops also. But, teak plantation maintained by Kerala Forest Department showed high abundance. High abundance was recorded in all plots of SEM followed by MDF and DF. The abundance of termites in semi-evergreen forest was as high as 9038 individuals m^{-2} in some plots. (Result based on statistical analysis is given in Chapter 5.2).

5.1.4. Discussion

Ants are important components of ecosystems, their biodiversity is incredibly high and these organisms are highly responsive to human impact, which obviously reduces its richness (Folgaraít, 1998). Ants occur throughout the world and constitute an important fraction of the animal biomass in terrestrial ecosystems (Hölldobler and Wilson, 1990). In the current study, ant diversity was high compared to termites and earthworms, with a record of 27 species. In ant communities, heterogeneity and resource availability have been reported as important processes to maintain species richness (Ribas and Schoereder, 2007; Ribas *et al.*, 2003). The reason may be same for increase in the number of species as structural heterogeneity increased based on this study. The number of species was high in polyculture farmlands, homegardens and semievergreen forests. These landuse types were rich in aboveground vegetation and with comparatively low disturbance regime (appendix Table A5). This heterogeneity in the vegetation would have contributed to the ant diversity by providing food and foraging habitats to different species.

Low diversity of ants was observed in annual crops, teak plantations under private ownership, pure areca and coconut mixed with perennials. This finding also supports the above hypothesis that the structural heterogeneity may positively contribute to the ant diversity. Monoculture plantation lack diversity of other vegetation, while in annual cropping system, continuous utilization of soil for cultivation along with low plant coverage as well as usage of pesticides and inorganic fertilizers might have affected the ant community. The present study is also in consensus with earlier studies (Gadagkar *et al.*, 1993; Basu, 1997; SunilKumar *et al.*, 1997; Malsch *et al.*, 2008; Sabu *et al.*, 2008), in which diversity of ants was high in landuse with high structural heterogeneity and availability of food and nesting places. Similar opinion was also made by Philpott and Armbrecht (2006) that traditional or less intensive system like agroforests serves as a refuge of ant biodiversity, which also provide ecosystem services like predation. King *et al.* (1998) also produced similar results, and during their study, undisturbed sites showed more ants than disturbed site.

Graham *et al.* (2004) studied the ant diversity across different disturbance regimes and their results support the present study in that, the highly disturbed area has fewer species, compared to moderately and less disturbed landuse systems. Species richness was greater in the moderately disturbed sites than in the lightly disturbed sites. Of the four main ecosystems studied here (annual crops, plantation, agroforestry and forest), annual cropping and plantation showed fewer number of species while agroforests showed more number of species than forests.

Estimation of diversity parameters (Table 5.1.5) showed that, forest and agroforestry systems didn't have remarkable difference (H'=2.23 and 2.56 respectively) and they are heterogeneous in nature (Simpson's diversity index D=0.87). Differences in the number of species may be due to poor sampling effort or the sampling may be done in different locations of a continuous forest stretch, while in the case of the agroforest the sampling plots are spatially unconnected. But in the case of plantation and annual crop, the difference is remarkable. If the number of species may be an indicator of habitat characteristics, agroforests and forest systems are 'healthy habitats' in terms of conserving ant biodiversity.

Table 5.1.5. Diversity parameters of ants in different ecosystems

	Species (N)	Dominance	Shannon (H')	Simpson (D)	Evenness (E_H)
Agroforestry	21	0.13	2.56	0.87	0.62
Plantation	8	0.24	1.70	0.76	0.69
Annual crops	2	0.60	0.59	0.40	0.90
Forests	12	0.13	2.23	0.87	0.78

Earthworms are another important macrofaunal component in the soil. They occupy a wide range of habitats and attain different sized communities under different ecological conditions. In the present study, seven species of earthworms coming under five families were collected. The number of species was low in agroforests, plantation and annual crops when compared to forest ecosystem (Table 5.1.3). It was observed that in natural systems, soil macrofauna is dominated by earthworms (Lavelle 1983., Lavelle and Pashanasi, 1989). But in cultivated soils, ploughing, tillage, application of biocides and absence of plant cover are responsible for the low densities (Barley, 1970; Low, 1972). In the present study also, in cultivated soil, diversity of earthworm was poor.

There are number of factors which affect the diversity of earthworms (Lindberg, 2003; Cole *et al.*, 2006) and earthworm community can indicate a number of soil characteristics (Edwards and Bohlen, 1996). Species number and ecological categories are favoured as key indicators of ecosystems (Paoletti, 1999). Atlavinyte (1990) claims that, changes in the number of species of earthworms and other soil organisms function as indicators of soil fertility or its exhaustion. In the current study, one species of epigeic earthworm was collected from semievergreen forest, while rest of the species was either endogeic or anecic. Habitually, *Megascolex* sp. is moisture loving and found in places with comparatively high organic content. This may be an indication of low organic content and poor moisture withholding capacity of other habitats. A semi-aquatic inhabitant species of earthworm *Glyphidrilus* sp. was collected from coconut landuse system. This indicates the prevailing condition of the previous landuse type, as mentioned earlier, most of the landuse systems were derived from paddy fields.

Several earthworm species termed as peregrine, have cosmopolitan distribution. Usually peregrine species are anthropochorous and are confined to disturbed, man-modified habitats. During this study a peregrine endogeic species, *P.corethrurus* was collected from most of the landuse systems studied. This worm possess a highly efficient digestive system and exceptional demographic traits (Zhang *et al.*, 1993, Barros *et al.*, 2001), allowing it to quickly colonize in disturbed places from where native earthworms have been removed (Lavelle and Pashanasi, 1989) and thrive in soils poor in organic matter. It is noteworthy that this species was also collected from some plots of forest ecosystems (SEF), which may be an indication of degradation. Studies indicate that (Gundale, 2002) such species can cause a significant reduction in the thickness of the 'O1' and 'O2' horizon of soil and a significant increase in the thickness of the 'A' horizon. Similar type of observations were also made by Burtelow *et al.* (1998) and showed that exotic earthworm modify the soil chemistry. Chauvel *et al.* (2000) reported that, *P.corethrurus* causes severe compaction of soil. This result is highly significant because exotic species can alter the forest floor and native vegetation. There was mounting evidence to show that exotic earthworm invasions are increasing worldwide, sometimes with significant effects on soil processes and plant communities (Hendrix, 2006). The reason that earthworm introductions appear to be facilitated by global commerce, both inadvertently with the importation of soil-containing materials (*e.g.*, agricultural and horticultural products) and intentional use in commercial applications (*e.g.*, waste management and land bioremediation). Probable reason for high population of *P.corethrurus* in the area may also be due to introduction of worms from other regions of the country through organic manure, livestock etc. There is ample reason to hold this view because the area of semi-evergreen forests, from where the exotic species were collected, there was loading and unloading of livestock from nearby States to the Kerala State.

Owing to prolonged use of land for agriculture and related activities, organic content is reduced and this may be the reason for abundance of species like *P.corethrurus* in such systems. But in some moderately and low disturbed systems, deep burrowing endogeic species *Drawida* sp.A was also collected. In forest systems especially in SEF, all the three functional groups of earthworms were present. *Lampito mauritii,* an indigenous earthworm species used for vermicomposting was collected from areca, annual crops and coconut systems. This may be due to the usage of compost in these agro-systems as a source of organic manure. In agriculture, agroforestry and plantation, endogeic species are more abundant. In some landuse systems (coconut mixed with perennials) the abundance of earthworm reached upto 639 individuals m^{-2}. Among the landuse studied, degraded forests have least abundance, which may be due to the poor plant regeneration and also the soil is exposed to prolonged dry period round the year, soil erosion due to bare top soil and associated low moisture content (appendix Table A5).

Termites are the major decomposers of tropical ecosystems. Studies on the richness and diversity of termite species and their ecological functions have increased in recent times. In the present study, six species of termites belonging to two families were collected. Of this, genus *Odontotermes* with two species and among this *Odontotermes obesus*-a mound building termite- was found to be distributed widely in the landuse systems studied. *Odontotermes feae* was collected from MDF, TE-KFD and SEF. *Trinervitermes* sp., a mound building termite, was collected from SEF. Throughout the agroforest and plantation except in teak, *O. obesus* was the only species collected, while in certain landuse systems termites were totally absent. There are ample evidences to show that, conversion of natural system to agricultural land decreases the belowground macrofaunal diversity (Lavelle, 1996; Jones *et al.*, 2003; Basu *et al.*, 1996).

Termites are the most important decomposers by virtue of their numerical dominance (Eggleton *et al.*, 1995, 1996). Disturbance affects termites by reducing diversity (especially of soil-feeding forms) and some species may reach crop pest status, owing to changes in the availability of organic matter. There was a negative or inverse relation between earthworm and termite density in different landuse systems (Decaëns *et al.*, 1994). Abundance of termite was found varying between habitats and across landuse systems and plots. It was reported that abundance and biomass showed strong dependence on the quantity of organic matter and nitrogen in the soil (Basu *et al.*, 1996) and in the current study two landuse systems (SEF and MDF) with comparatively high organic matter (appendix Table A5), termite showed high abundance and diversity. This supports the previous findings that favourable soil conditions enhance soil macrofauna.

Studies have shown that landuse change and fragmentation of existing landscape have severe negative impact on termite community (Jones *et al.*, 2003; Gathorne-Hardy *et al.*, 2006). The agriculture system lack understory vegetation, wood remnants and many other materials which provide niche for successful establishment of termites. It is suggested that (Jones *et al.*, 2003) use of reduced-impact logging techniques and leaving dead wood to decay *in situ*, provide a good refuge for termites. Experimental evidences also showed that wood remnants enhanced fast assembly and successful colonization of termites in disturbed land (Davies *et al.*, 1999). It was also reported that, aboveground vegetation and habitat heterogeneity have positive effect on termite community (Gillison *et al.*, 2003). This can be used as a good strategy for ecosystem recovery and have great impact on soil fertility and ecosystem function.

Chapter 5.2

Spatial distribution of soil fauna

CHAPTER 5.2: Results

5.2. Spatial distribution of soil fauna

5.2.1. Influence of habitat heterogeneity and landscape structure

Habitat fragmentation or the separation of a landscape into various land uses results in numerous, small and disjunctive habitat patches, which is a key factor in the loss of biodiversity. Habitat fragmentation affects plant and animal populations at several scales. Fragmentation typically occurs when land is converted from one type of habitat to another. When native vegetation is cleared for agriculture, habitats which were once continuous become divided into fragments. After intensive clearing, the separate fragments tend to be very small islands isolated from each other by crop land and pasture. Thus ecological connectivity is central to understanding the potential for cumulative effects to impact upon diversity.

Altogether, 17 parataxonomic units (higher taxonomic groups) were identified from the 15 different landuse systems. This includes earthworms (Annelida), termites (Isoptera), ants (Hymenoptera), adult beetles and larvae (Coleoptera), earwigs (Dermaptera), Orthoptera (hoppers, crickets, mole crickets), Hemiptera (bugs, coccides, cicadas etc.), woodlice (Isopoda), centipedes (Chilopods), millipedes (Diplopods), Diptera larvae, Decapods, Mollusca, Blattids, Thysanura and spiders (Arachnida).

A single linkage cluster analysis was conducted on macrofauna abundance (Fig. 5.2.1), and it was clear from the cluster analysis that, forest landuse types (SEF, MDF and DF) were distinct from rest of the landuse types. Considering the results of cluster analysis and based on knowledge of biophysical conditions and other aspects of each landuse type studied, the 15 landuse systems were grouped as ecosystems *viz.*, agricultural, agroforestry, plantations and forest ecosystems (Table 4.1).

Agriculture system includes annual cropping systems like rice and vegetables like banana, tapioca etc. Cultivation was more or less seasonal and mainly depended on availability of water and there was intensive usage of chemical fertilizers and pesticides (Table 5.3.1). Plantation consists of teak, rubber, areca, coconut, etc. Homegardens, polyculture farms and other perennials with mixed cultivation practices were all grouped under agroforestry, following the broader definition of agroforestry, which are complex systems looking like and functioning as natural forest ecosystems, but are integrated into agricultural management systems. Forest ecosystem includes semi-evergreen, moist deciduous and degraded forests.

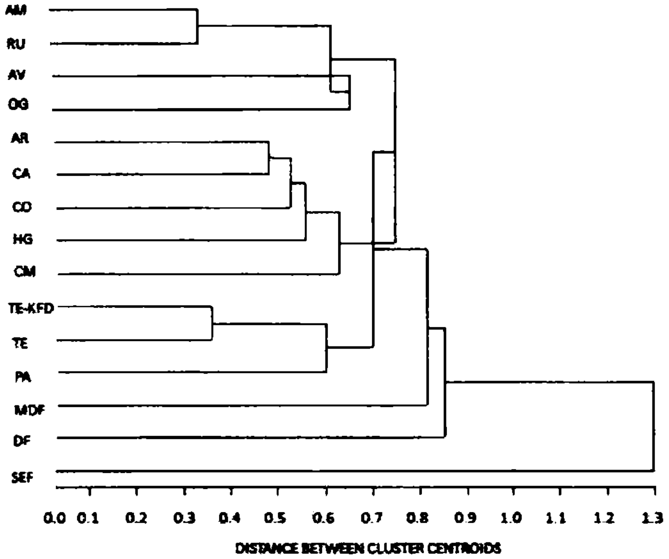


Fig. 5.2.1. Single-linkage cluster analysis of macrofauna abundance

5.2.1.1. Variation among ecosystems

5.2.1.1.1. Variation in the richness of supra-specific taxa

The number of highest taxa per monolith significantly varied (χ^2 = 79.1, P<0.0001) across ecosystems. The lowest and highest number of taxa was recorded in annual crop fields and forests, respectively (Fig. 5.2.2). Although agroforests and plantations had slightly higher number of taxa than annual crop fields, the difference between these ecosystems were not significant (Fig. 5.2.2).

5.2.1.1.2. Variation in abundance of supra-specific taxa

The total number of individuals (all taxa combined) per monolith was significantly higher (χ^2 = 195.4, P<0.0001) in forest ecosystems than all other ecosystems. Annual crop fields showed the lowest, while agroforests and plantations were comparable, but significantly higher than annual crop fields (Fig. 5.2.2).

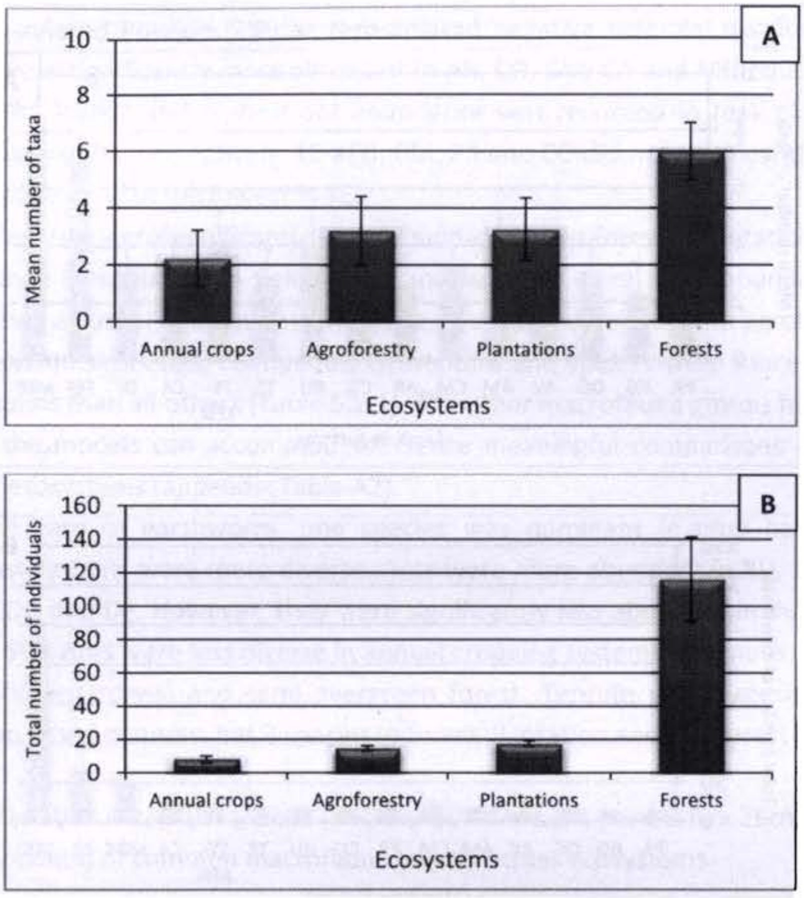


Fig. 5.2.2. Mean number of higher taxa (A) and total number of all individuals (B) per monolith recorded in various ecosystems. Error bars are model-based standard errors of means

5.2.1.2. Variation among landuse practices

5.2.1.2.1. Variation in richness and abundance

The richness in supra-specific taxa significantly varied (χ^2 = 159.1, P<0.0001) with land-use practices (LUPs). The lowest number of taxa was recorded in coconut monoculture (CO) plantations, while the highest was in moist deciduous (MDF) and semi-evergreen forests (SEF), respectively (Fig. 5.2.3). Compared to the deciduous and semi-evergreen forests, all other landuse practices had significantly lower number of taxa per monolith (Fig. 5.2.3).

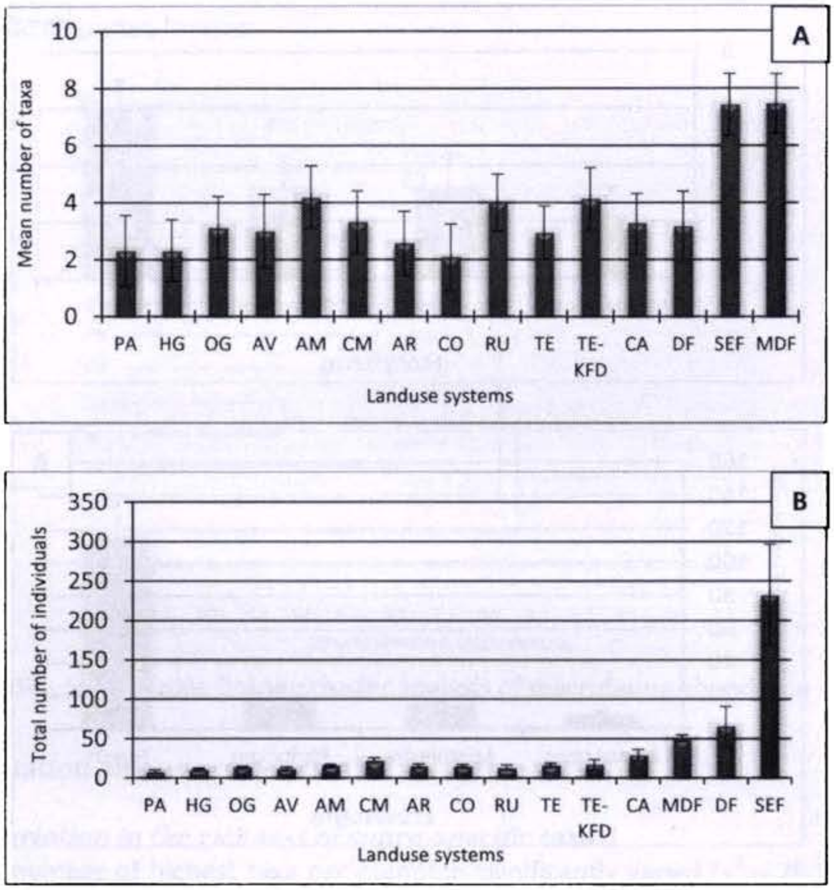


Fig. 5.2.3. Mean number of higher taxa (A) and total number of all individuals per monolith (B) recorded in various land-use practices. Error bars are model-based standard errors of means. Landuse codes are same as Table 4.1

5.2.1.2.2. Variation in abundance

Most of the macrofaunal counts show many zeros (appendix Table A1). Therefore, the zero-inflation parameter was estimated for all counts to select the statistical model appropriate for each taxon. This indicated that the proportion of extra zeros was lower than 3 per cent in earthworm, ant and beetle count data. Comparison of Akaike's information criterion (AIC) values also confirmed that the standard negative binomial distribution (NBD) fits the earthworm, ant and Coleoptera (larvae + adult beetles) count data better than the

Poisson, zero-inflated Poisson (ZIP) or zero-inflated negative binomial distribution (ZINB). Earthworms were significantly more abundant in AR, CO, CM, CA and MDF than in all other treatments. The lowest and highest ant abundance was recorded in teak plantation and semi-evergreen forests, respectively. TE-KFD, CM, PA and CO did not significantly differ from the land-use practice with the lowest in TE.

Earthworms were significantly more abundant in agroforests, plantations and forest ecosystems than in annual crop fields. Ants and termites were more abundant in forest ecosystems than all other ecosystems. Millipedes were more abundant in agroforestry than all other ecosystems. Beetles, centipedes, Orthoptera and spiders were more abundant in forest ecosystems than all others (Table 5.2.1). The other macrofauna groups had more zero counts than the models can accommodate. Hence meaningful comparisons could not be made among ecosystems (appendix Table A2).

In the case of earthworm, one species was dominant in crop based systems, whereas forest systems were more diverse. Ants were more abundant in RU, AR, CA, MDF, HG, AM, AV, OG and DF. However, they were significantly less abundant in these land-uses compared to SEF. Ants were less diverse in annual cropping systems and more diverse in the agroforests (homegardens) and semi evergreen forest. Termite was represented by one species in crop based systems, but 3 species in forest plantation and 5 in forest systems.

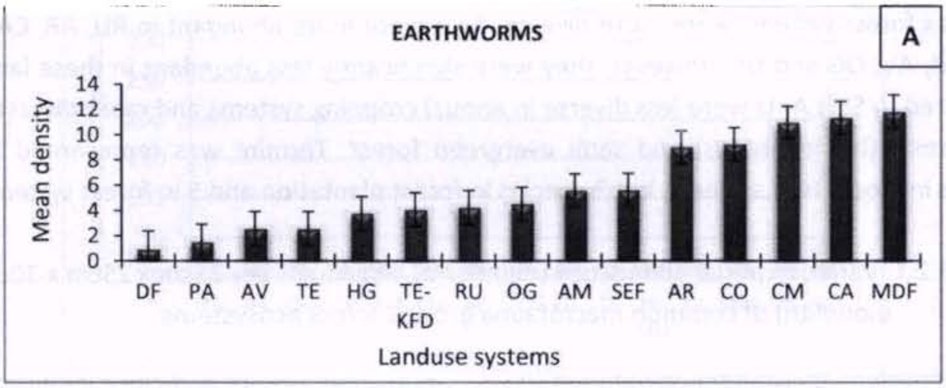
Table 5.2.1. Variation in the abundance (number of individuals per 25cm x 25cm x 30cm monolith) of common macrofauna groups across ecosystems

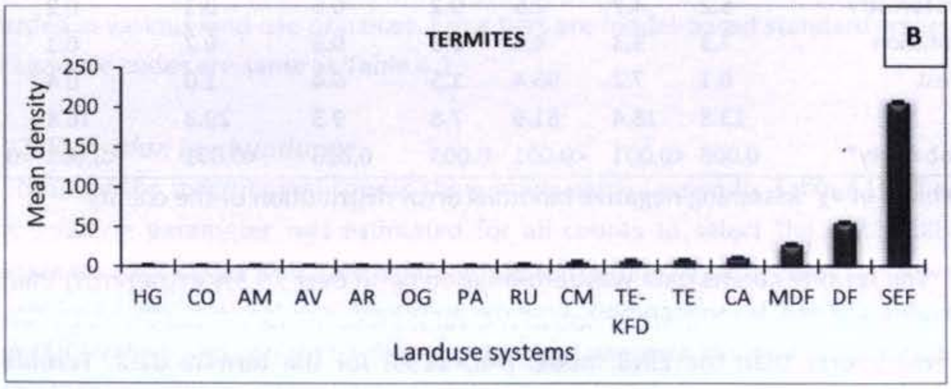
Ecosystem	**Earthworm**	**Ant**	**Termite**	**Beetle**	**Millipede**	**Centipede**	**Orthoptera**	**Spider**
Annual crop	1.5	2.5	1.0	0.2	0.1	0.5	0.0	0.1
Agroforestry	5.2	4.7	2.5	0.2	0.6	0.3	0.2	0.1
Plantation	7.3	3.3	4.4	0.3	0.3	0.2	0.1	0.2
Forest	6.1	7.2	96.4	1.5	0.4	1.0	0.4	0.6
χ^2	13.8	18.4	81.9	7.8	9.3	29.3	16.8	24.1
Probability*	0.003	<0.001	<0.001	0.003	0.026	<0.001	<0.001	<0.001

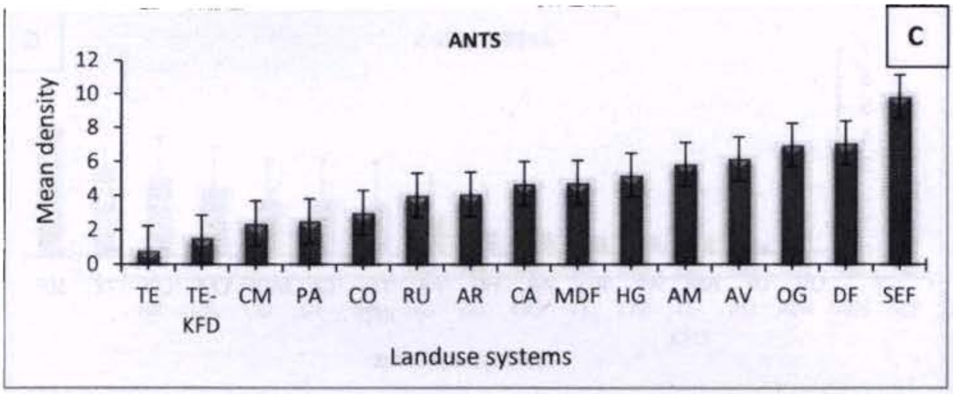
*Probability of $>\chi^2$ assuming negative binomial error distribution of the counts

The termite counts data was zero-inflated (with over 79.3% extra zeros) than can be accounted for by the NBD. Comparison of AIC values also indicated that the NBD (with AIC = 1198) was poorer than the ZINB model (AIC=1190) for the termite data. Termites were found in significantly larger numbers in SEF, while they occurred only in small numbers in HG, CO, AV, AR, OG and PA.

It was observed that, neither the standard Poisson nor the negative binomial distributions fitted millipede, centipede, Dermaptera, Isopoda, Orthoptera and spider abundance data collected across land-use practices. Therefore, zero-inflated models were considered more appropriate for these taxa. The ZIP model fitted the millipede count data better than the ZINB. Estimated zero-inflation probabilities indicated 72 and 65 per cent extra zeros in the millipede count data assuming the ZIP and ZINB models, respectively. In the case of centipedes, the ZIP and ZINB models were equally good (AIC=407.9 for ZIP and 407.5 for ZINB). However, the ZINB model with a lower zero-inflation probability (0.48) accommodated more zeros in the count than the ZIP (zero-inflation probability 0.60) (Figs. 5.2.4 A-K).






ANTS
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Mean density
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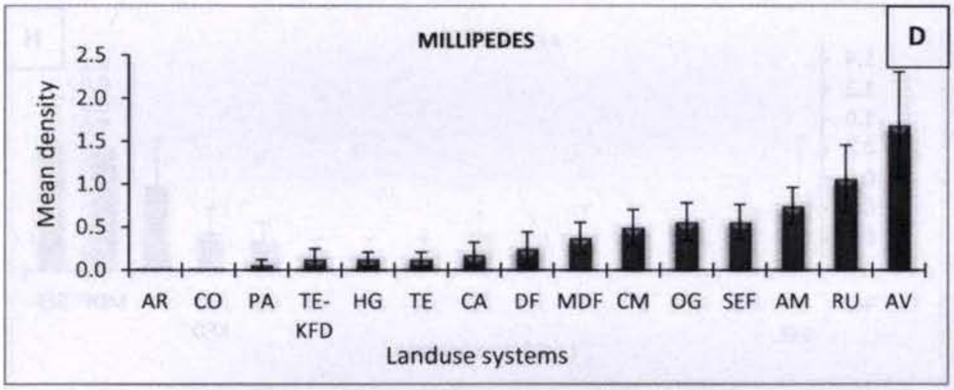
SEF
Landuse systems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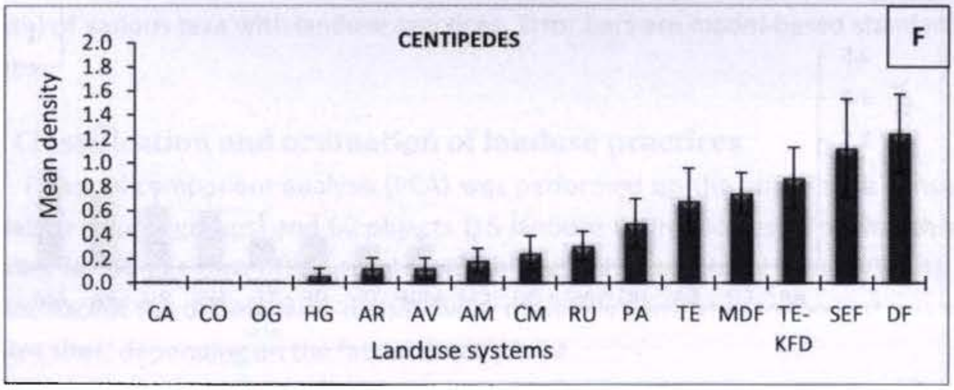
Landuse systems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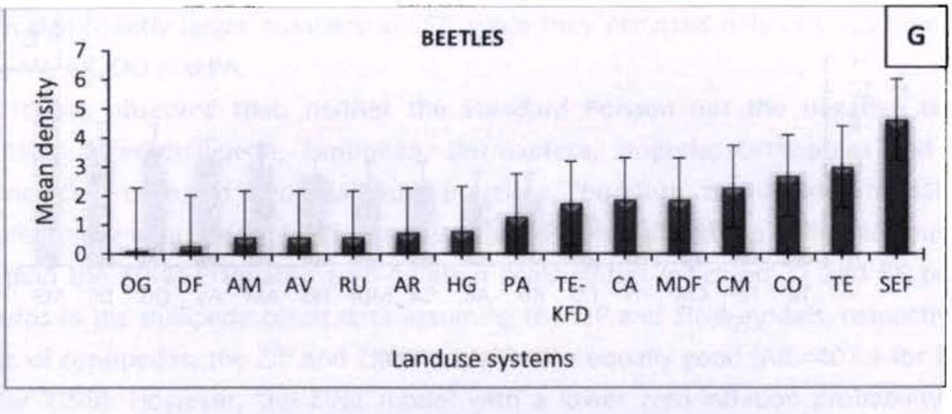
Landuse systems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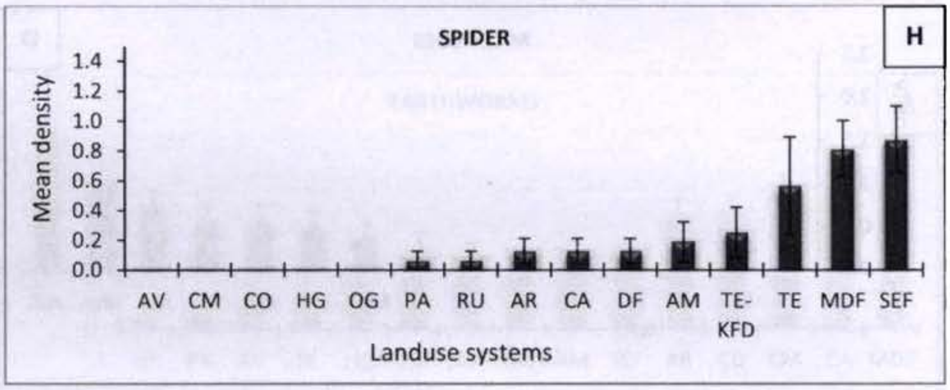
Landuse systems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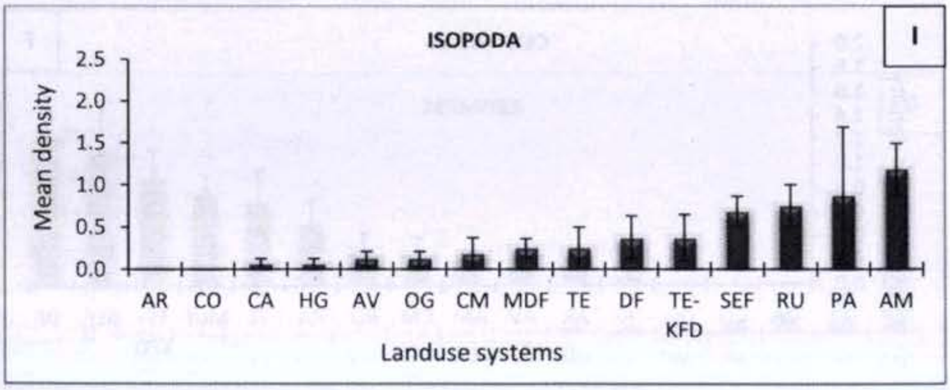
Landuse systems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Landuse systems

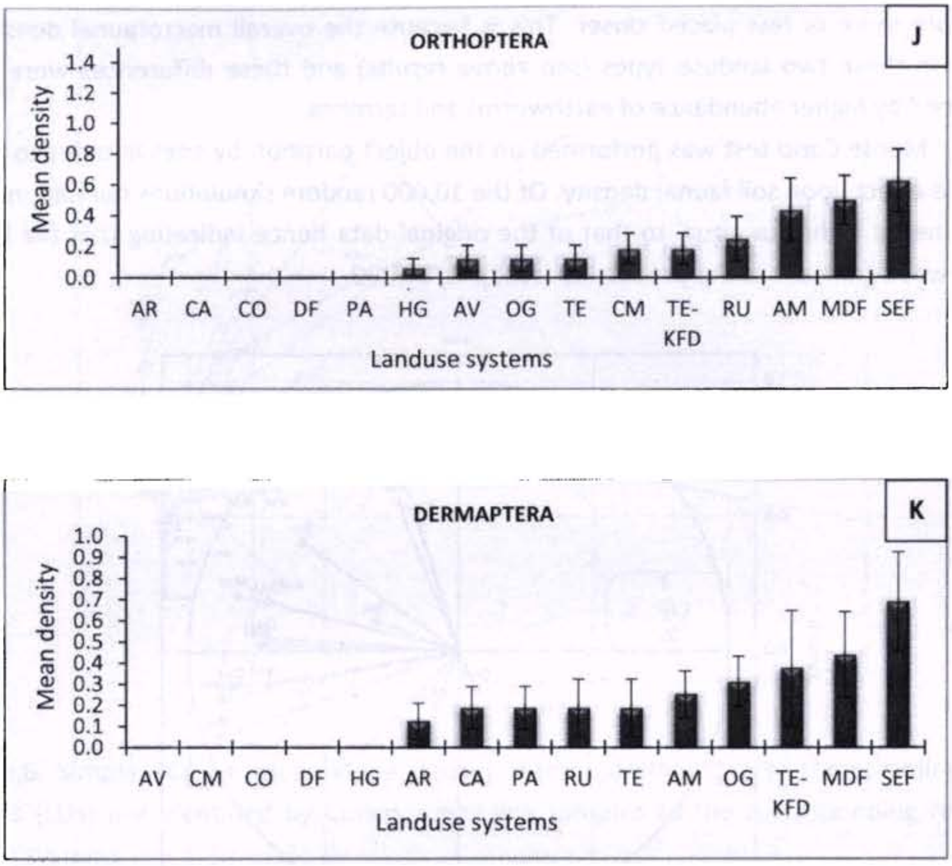

Fig. 5.2.4. Variations in the mean density (number of individuals per 25cm x 25cm x 30cm monolith) of various taxa with landuse practices. Error bars are model-based standard errors of means

5.2.2. Classification and ordination of landuse practices

Principal component analysis (PCA) was performed on the above data consisting of 17 variables (faunal groups) and 60 objects (15 landuse x 4 replicates). The first three axes accounted for 55 per cent of the total variance (Fig. 5.2.5, appendix Table A3, A4). All the variables, except the diptera larva density were positively correlated to the first axis and this separates sites, depending on the faunal density.

Site ordination (Figs. 5.2.6, 5.2.7) mainly separated objects as a function of the land-uses. Therefore, it revealed that land management chiefly affected the global density (axis 1). The two landuse types (MDF and SEF) are placed very distinctly, while other landuse types are more or less placed closer. This is because the overall macrofaunal density was higher in these two landuse types (see above results) and these differences were mainly explained by higher abundance of earthworms and termites.

Monte Carlo test was performed on the object partition by sites in order to test for landuse effect upon soil faunal density. Of the 10,000 random simulations realised, none led to an inertia higher or equal to that of the original data hence indicating that the landuse effect was significant at the probability level p<1/10,000.

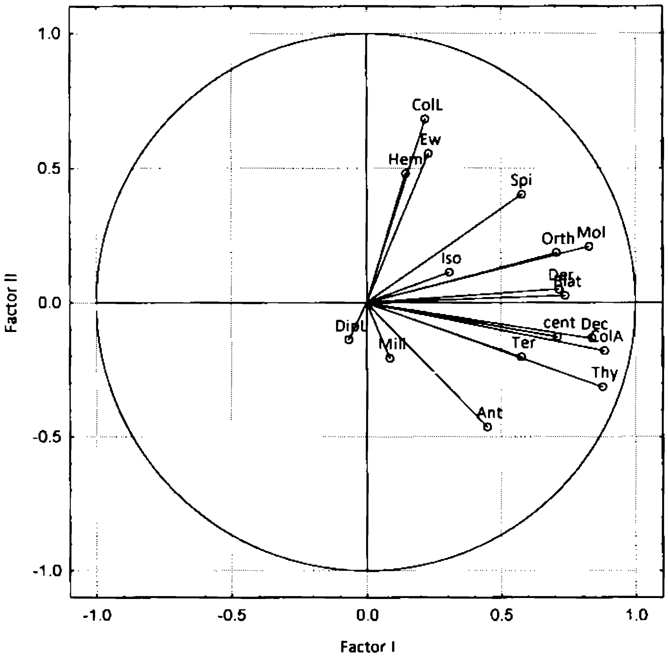

Fig. 5.2.5. Simple PCA on macrofaunal density. Correlation circle for the axes 1 and 2, respectively (Two dimensional canonical graph for a normed PCA (correlation circle): the direction and length of arrows show the quality of the correlation between variables and between variables and principal components)

Within-site ordination of different landuse systems (Figs. 5.2.6, 5.2.7) shows high spatial variability of soil fauna in different landuse systems studied. The result shows spatial segregation of different plots of landuse system. This may be due to the over dispersion of the fauna with many zeroes in the count data.

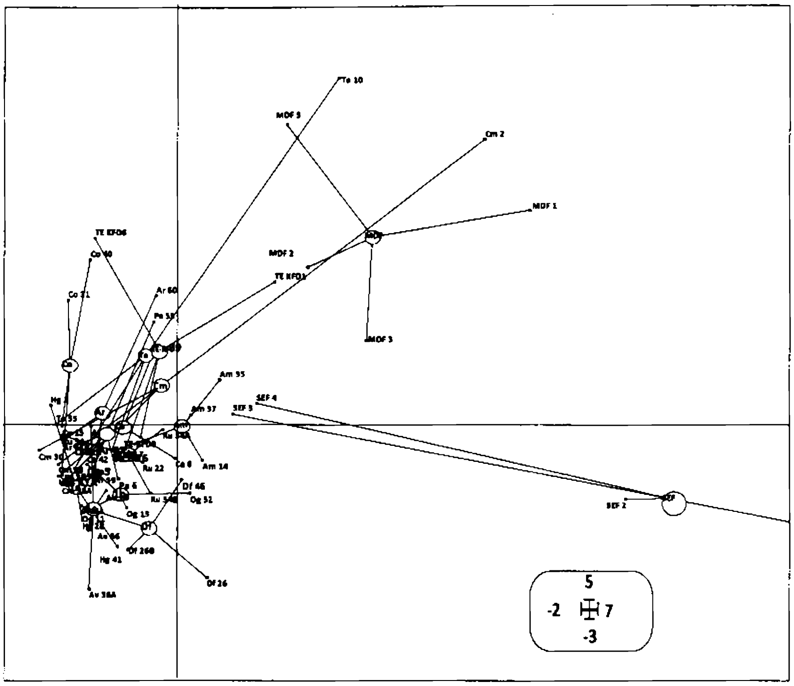

Fig. 5.2.6. Simple PCA on macrofauna density. Factorial plane 1-2 of the sampling sites. Samples (LUs) are identified by Circles. Lines link samples to the corresponding replicate landuse systems

The first three axes PCA accounting for 55 per cent of the total variation, a biplot is created with first two axes (Fig. 5.2.8). Those landuse systems, which had high overall abundance of most macrofauna viz., teak plantation under Forest Department, teak plantation under private ownership, moist deciduous forest and semi-evergreen forest, are in the upper right panel of the bi-plot (Fig. 5.2.8). The overall abundance is more in those landuse systems, which form a distinct group in PCA.

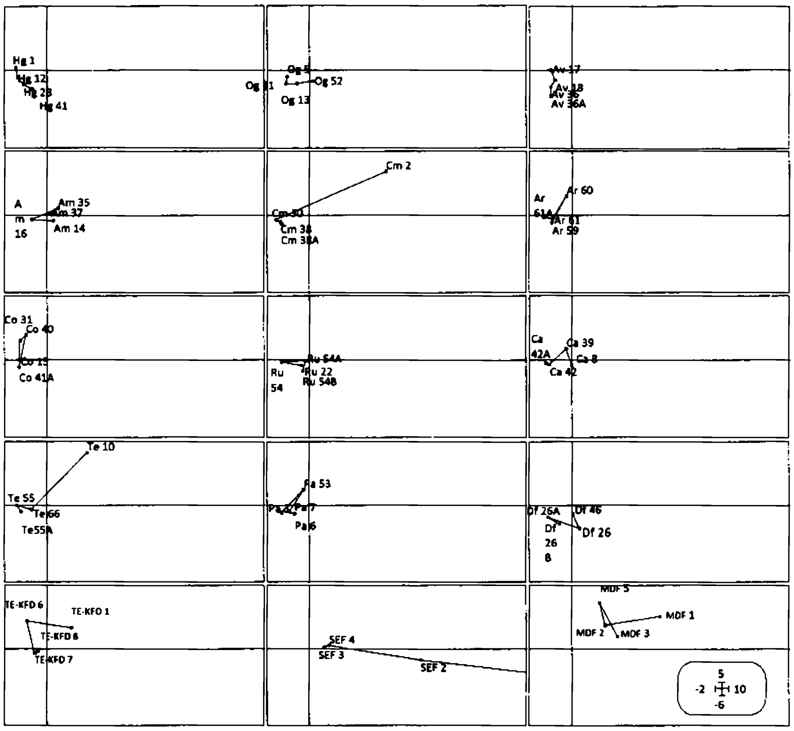

Fig. 5.2.7. Within site PCA of the macrofauna density. Factorial plane (1-2) of sampling LUs, trajectories separated by replicates.

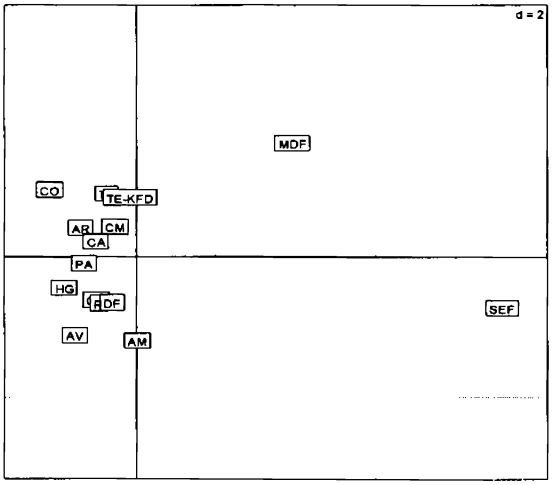

Fig. 5.2.8. Row coordinates of PCA correlation matrix, based on correlation matrix PCA landuse averaged data (Axis 1and 2)

The overall result of correlation metrics PCA (factorial plane 1 and 2) is given below (Fig. 5.2.9). The result of PCA (Figs. 5.2.5, 5.2.8 and 5.2.9) shows that the site SEF is expected to have larger average values for termites, Thysanura, Decapoda because these species (and most of the other species) and this site occur in the same direction from the centre. By constructing perpendicular line for each site showing their projection onto this arrow, it gave an indication of differences in abundance between the sites. Sites SEF and MDF are projected farthest from the origin in the direction of the species vector. It should be expected that these sites have greater abundances for the particular species than the other sites. Sites CO and AR are projected at the opposite side of the species vector, expect lower than average abundances for these sites. When checking the original species matrix (appendix Table A1), it can be confirmed that this interpretation is a good approximation of the actual situation. While examining correlation among species (Fig. 5.2.5), most of the species are positively correlated.

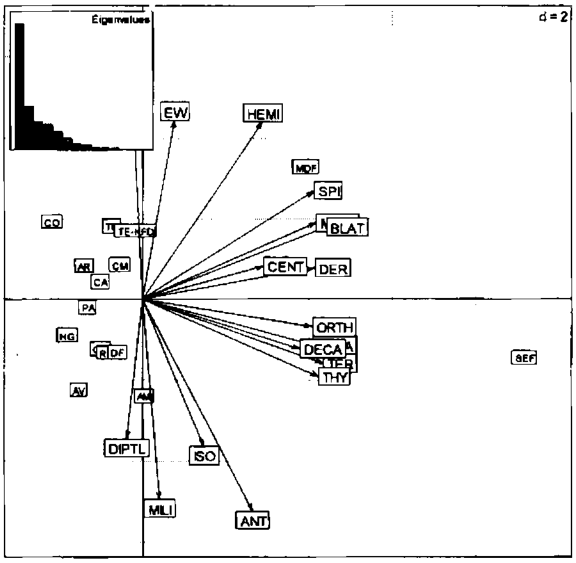

Fig. 5.2.9. Final scatter for landuse averaged data. Eigenvalues are shown in box (Axis 1and 2). Variables are symbolized by arrows and they are superimposed to the individuals display. The scale of the graph is given by a grid, which size is given in the upper right corner. Here, the length of the side of grid squares is equal to five. The eigenvalues bar chart is drawn in the upper left corner, where in the two black bars are the two axes used to draw the biplot and grey bars are axes that were kept in the analysis, but not used to draw the graph.

5.2.3. Discussion

The good fit of the negative binomial distribution (NBD) and zero inflated negative binomial (ZINB) to the count data on earthworms, ants, beetles and termites indicate spatial contagion in the density distribution of these taxa. This is also an indication of habitat heterogeneity which influences the distribution and abundance of macrofauna. The abundance and diversity of soil animals is often influenced by a wide range of management practices (Wallwork, 1976; Curry, 1994; Wardle, 1995) including tillage, treatment of crop residues, crop rotation, application of pesticides and fertilizers (Baker, 1998). In this study, taxonomic richness and abundance of macrofauna was higher in the tree-based systems compared to the annual crops. This is probably because trees and shrubs in forest ecosystems and agroforestry systems provide more favourable microclimate to soil macrofauna. These findings are in agreement with those of Sileshi and Mafongoya (2007). Trees bring about a whole complex of environmental changes, affecting light, air temperature, humidity, soil temperature, soil moisture content, wind movement, and pest and disease complexes (Sileshi *et al.*, 2007, 2008). These changes have impacts both on plants and a wide array of soil macrofauna (Sileshi and Mafongoya, 2007).

Structural and functional heterogeneity, spatial and temporal heterogeneity, perennialism etc., are some important ecosystem properties of agroforestry dynamics (Nair *et al.*, 2008) and they show similarity with natural forests in species diversity, richness and other attributes (Kumar and Nair, 2006; Mohan *et al.*, 2007). As the structural complexity of above-ground vegetation increased from annual crops to polyculture farms, it has contributed to the spatial contagion of soil faunal abundance, which was clearly shown in the ordination diagrams (Figs. 5.2.6, 5.2.7), the forest ecosystems (SEF and MDF) are spatially distinct from rest of the habitats. The heterogeneity of the habitat probably provided numerous niches to the soil fauna, supports more food availability and shelter, which in turn could lead to higher taxonomic richness of fauna in agroforestry systems and natural forests. The lower diversity and abundance of soil macrofauna in the intensively managed annual cropping systems could be due to poor heterogeneity and food resources. In the annual cropping systems, the land is utilized year round for growing crops compared to the agroforestry systems and forest ecosystems. Land is also utilized for many years for the same purpose with intensive usage of fertilizer and pesticide in some cases. Giller *et al.* (1997) show very close correlation between increasing agricultural intensification and reduced soil biodiversity. This intensification may also lead to soil erosion, which in turn can reduce the abundance and diversity of soil biota by physically removing them, destroying their microhabitats and changing the microclimatic conditions within the soil (Harvey, 1996).

Within site PCA (Figs. 5.2.6, 5.2.7) shows low abundance of macrofauna in annual crops. Abundance increased in concordance with heterogeneity of the landuse and was maximum in forest ecosystem. Spatial representation of the normalized variables shows that the individual faunal groups have aggregated distribution between and within a landuse system and between different plots of a landuse system. Some plots have a good representation, but others have low value than the overall mean abundance. It is generally thought that soil fauna is spatially aggregated and has a clubbed distribution pattern (Usher, 1976; Usher *et al.*, 1982; Rossi and Lavelle, 1998; Jiménez *et al.*, 2001). There are many reasons for the spatial aggregation, from local habitat characters to many environmental features and intrinsic features of fauna itself.

Indeed, the structural complexity and associated micro-niches provided by the trees and under-storey vegetation could greatly enhance the belowground communities. Management practices also have great influence in diversity and distribution of the soil faunal communities. This was indicated by the higher abundance of macrofauna in natural forest ecosystems and agroforestry systems. As expected, the natural forests have less human interference and have greater abundance of soil fauna. In agroforestry systems and plantations, soil disturbance is less and also use of inorganic fertilizer and pesticides minimal. On the other hand, the high input of green manure and litter biomass could increase abundance of macrofauna (Sileshi and Mafongoya, 2007).

The sampling covered different ranges of agricultural intensification-from intensive annual cropping systems to less managed, highly stratified polyculture and homegarden agroforestry systems- and the results indicate that there was increasing diversity and abundance of soil fauna from intensively managed annual cropping systems to less intensively managed agroforests and natural forest ecosystems. In conclusion, the results support the growing body of literature that points towards the negative impact of native vegetation clearance, habitat loss and fragmentation on biodiversity. It also supports the hypothesis that anthropogenic disturbance has negative impacts on soil fauna.

Chapter 5.3

Influence of edaphic, climatic and management aspects on soil fauna

5.3. Influence of Environmental and Management factors

5.3.1. Soil and Climatic pattern

Elucidating the pattern of community assemblage is a challenge in community ecology. To construe the underlying pattern, ecologists often deal with environmental variables, which may have strong impact on the diversity and distribution of organisms in an ecosystem.

Relation between soil biotic biodiversity and habitat are the main issues in soil ecology research. Losses of natural or semi-natural habitat to simplified habitats are major concerns in soil biodiversity, which alter the soil conditions. Interpretation of structural dynamics of assemblage of soil organisms in relation to the prevailing environmental conditions draws inference on the spatial influence of abundance of organisms.

5.3.1.1. Edaphic factors of the study area

The variables studied are grouped into two: soil parameters and vegetation characteristics. Soil physico-chemical parameters includes pH, organic carbon (OC), total nitrogen (N), phosphorous (P), exchangeable cations like potassium (K), calcium (Ca) and magnesium (Mg), moisture content (%), bulk density, sand, silt, clay content. Vegetation parameters include tree, herb and shrub density. Mean precipitation, temperature and humidity were also accounted in the study (appendix Table A5). Among these variables temperature, humidity and rainfall were exempted from the direct gradient analysis.

There were differences in soil physico-chemical properties between man-made and natural systems. Vegetation structure and management practices also varied among sampled habitats (appendix Table A5). The soil moisture content showed wide variation (between 9.1-33.8%) across landuse types, higher value of soil moisture was observed in SEF and CM, while lowest value (9.1%) was observed in DF. Among forest ecosystems, highest and lowest moisture content was observed in SEF and DF respectively. In agroforestry systems, highest soil moisture was recorded in CM and lowest in AV. In plantations, this trend was not prominent, although AR showed higher moisture content.

In general, soil was acidic in the study area. There was not much variation in soil pH. Variation in pH in forest ecosystems was negligible, while there were small variations among agroforests and plantations. This was also true for plantation. Organic carbon content showed variation among different landuse systems. Highest OC content was observed in SEF (2.27%) while lowest values were obtained for HG and PA. Both forest systems (SEF and MDF) showed higher organic content than rest of the landuse types.

Total nitrogen content was relatively low and highest values were recorded in HG, RU, SEF and MDF. But phosphorous content was higher in TE and lower in DF. As in the case of nitrogen, potassium content was also relatively low and highest content was recorded in soil of CA. There were also differences in other parameters studied like, Ca, Mg, bulk density, particle density. Vegetation data showed a remarkable difference among landuse systems. Tree density varied from 0 to 1300 individual per ha and highest tree density was recorded in SEF. Herb and shrub density also varied across landuse systems.

5.3.1.2. General climatic pattern

Rainy period ranged from May to November (Figs. 5.3.1, 5.3.2). Typical rainfall pattern was observed for the last 10 years, with two-peaks-South-West monsoon (May to September) and North-East monsoon (October and November). Relative humidity also increased correspondingly with peak value in June and July. There was not much difference in the total precipitation and total number of rainy and non-rainy days (Fig. 5.3.2). Total precipitation was low in 2002 and 2003 (appendix Table A6).

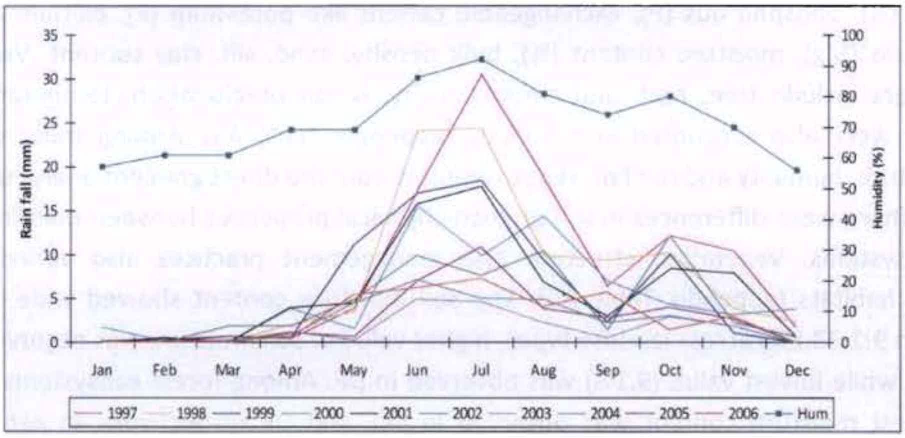

Fig.5.3.1. Mean precipitation and month-wise humidity recorded in the study area

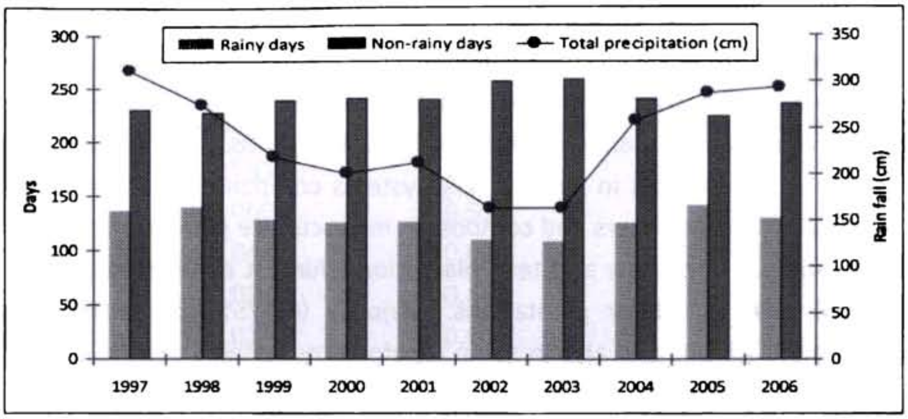

Fig. 5.3.2. Total rainfall, rainy and non-rainy days in the study area

5.3.2. Management attributes of landuse systems

Landuse intensity and habitat properties are important drivers of soil faunal biodiversity. To examine the influence of land management on soil macrofauna biodiversity, 12 management attributes were identified and information gathered. Among this, application of fertilizer and pesticide is thought to be most important attributes, hence quantified information on these attributes were collected (Table 5.3.1).

Table 5.3.1. Fertilizer and pesticide usage in different landuse systems

Ecosystem	**Land use**	**Quantity of fertilizer (kg ha^{-1})**			**Percentage of farmers using pesticides**			
		Inorganic	**Compost**	**Green manure**	**Bio pesticides**	**Chemical**	**Both**	**None**
Natural forest	SEF	0	0	0	0	0	0	100
	MDF	0	0	0	0	0	0	100
	DF	0	0	0	0	0	0	100
Plantation	TE KFD	0	0	0	0	0	0	100
	AR	236	3347	0	0	0	0	100
	CO	244	3645	417	0	33	0	67
	RU	217	1037	0	0	100	0	0
	CA	0	0	0	0	0	0	100
	TE	0	0	0	0	0	0	100
Annual crops	PA	437	250	0	0	75	25	0
Agroforestry	HG	71	2905	1476	0	29	29	43
	OG	502	1386	2944	0	40	20	40
	AV	111	1736	1667	0	67	0	33
	AM	407	1845	3750	33	33	0	33
	CM	167	1421	1000	33	67	0	0

Most of the farmers used inorganic or organic fertilizers as well as pesticides in plantations, agroforestry systems and annual crop fields (Table 5.3.1). Farmers applied green manure in all the agroforestry systems. On the other hand, none of the monoculture plantations received green manure except coconut plantations. Compost and green manure were applied at higher rates in agroforestry systems compared to annual crops. Farmers applied both inorganic fertilizers and compost in monoculture plantations of areca, coconut and rubber, but not to cashew and teak plantations. Almost all farmers applied pesticides (mainly herbicides) in rubber plantations. Majority (67-75%) of farmers also applied pesticides in annual crops and also in some agroforestry systems such as areca mixed with annual crops and coconut mixed with perennial crops.

5.3.3. Interpreting the variation

The results of canonical correspondence analysis (CCA) showed that, the measured environmental variables accounted for main variation in the soil macrofauna (Table 5.3.2a,b). The first CCA axes account for 75 per cent of the total variation (Table 5.3.2b), which could explain 75 per cent of the variation in the soil fauna by the measured variables. Eigenvalues and species environment correlation (Table 5.3.2a) show that, species environment correlation is very high. The first axis of CCA is negatively correlated with OC (r=-0.70), coarse sand (r=-0.73) and clay (r=-0.80) (Table 5.3.3).

Table 5.3.2a. Sum of eigenvalues and species environment correlation of CCA

Axes	**1**	**2**	**3**	**4**	**Total inertia**
Eigenvalues	0.54	0.06	0.04	0.02	1.34
Species-environment correlations	0.93	0.63	0.46	0.65	
Cumulative percentage variance					
of species data	40	44.5	47.6	49.3	
of species-environment relation	74.7	83.1	88.9	92.1	

Table 5.3.2b. Eigenvalues of CCA

Axes	Eigenvalue	Cumulative eigenvalue	Cumulative %
1	0.536	0.536	74.7
2	0.0608	0.597	83.1
3	0.0413	0.638	88.9
4	0.0230	0.661	92.1
5	0.0152	0.676	94.2
6	0.0132	0.689	96.0
7	0.0106	0.700	97.5
8	0.00766	0.708	98.6
9	0.00303	0.711	99.0
10	0.00262	0.713	99.4
11	0.00218	0.715	99.7
12	0.000970	0.716	99.8
13	0.000693	0.717	99.9
14	0.000526	0.718	100
15	0.000890	0.718	100
16	0.0000432	0.718	100

Table 5.3.3. Correlation coefficient of environmental variables and first three axes of CCA

Parameters	Axis I	Axis II	Axis III
pH	0.19	-0.28	-0.31
OC	-0.70	-0.36	0.23
N	-0.42	0.03	-0.07
P	0.54	-0.25	-0.22
K	0.08	0.16	0.14
Ca	-0.29	-0.29	0.22
Mg	0.04	-0.49	0.15
Moist	-0.38	0.06	0.00
Bulk Density	0.26	-0.20	-0.15

Sand-Fine	0.42	0.22	0.39
Sand-Coarse	-0.73	-0.04	-0.20
Silt	0.19	-0.12	0.10
Clay	-0.80	-0.26	-0.07
Tree	-0.47	0.09	-0.20
Shrub	0.13	0.14	-0.21
Herb	0.33	-0.05	0.28

The ordination diagram of soil fauna against environmental variables shows the pattern of spatial distribution of fauna across different landuse systems (Fig. 5.3.3a,b).

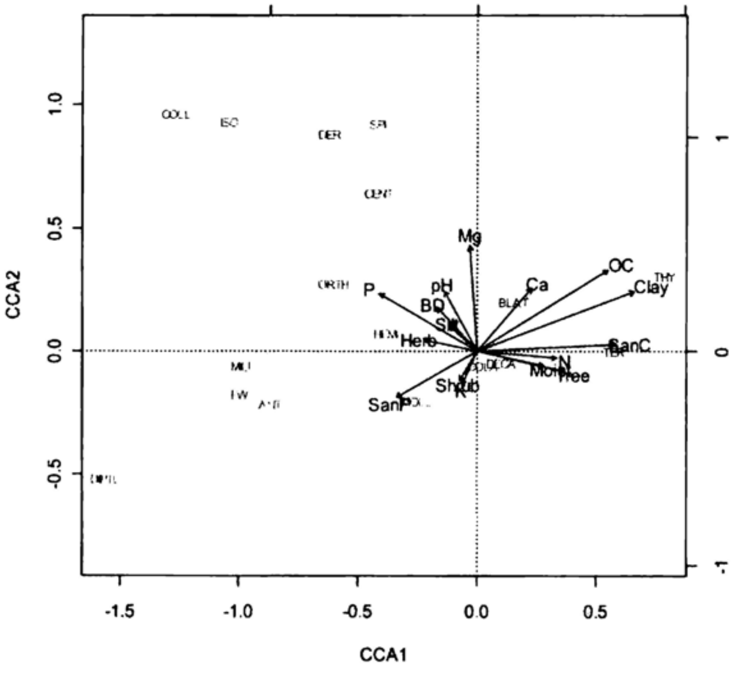

Fig.5.3.3a. CCA ordination diagram with soil fauna and environmental variables (arrow)

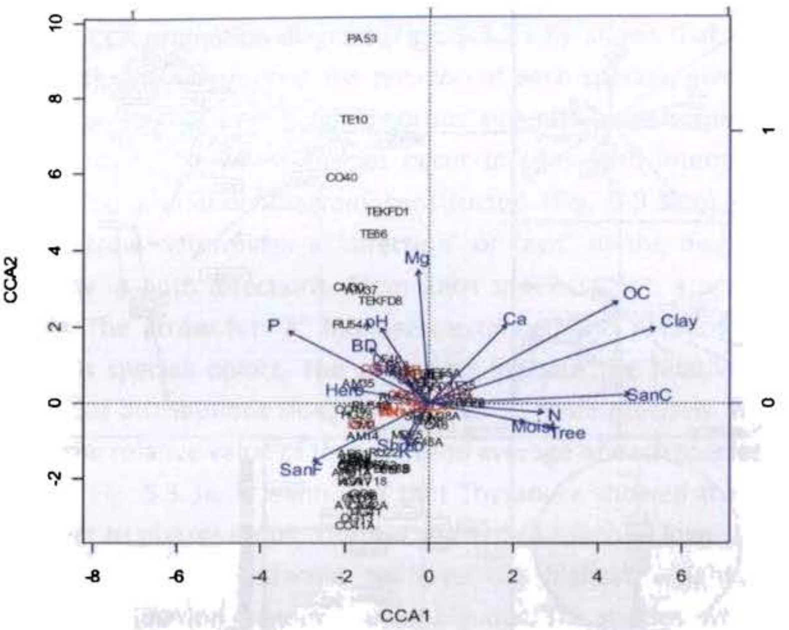

Fig. 5.3.3b. CCA triplot showing species, sites and environmental variables, site scores as weighted average of species scores

Figure 5.3.4 shows environmental variable loadings and correlations, projection of the axis of species analysis and a biplot of site scores superimposed with their predictions by environmental variables. Canonical loadingsaremeasure of the simple linear correlation between the independent variables and their respective canonical variates. These can be interpreted like factor loadings, and are also known as canonical structure correlations. Eigenvalues are an estimate of the amount of shared variance between the respective optimally weighted canonical variatesof dependent and independent variables. Canonical variates are linear combinations that represent the weighted sum of two or more variables.

To test the degree of association between the two data matrices (soil fauna and environmental variable), PROcrustean randomization TEST (PROTEST) was used. In this analysis, matrix is subject to reflection, rigid rotation, translation, and dilation to minimize the sum of the squared residual deviations between points for each observation and the identical observation in the target matrix. This is a classical Procrustes approach to matrix analysis, which determines whether the sum of residual deviations is less than that expected by chance.The result was significant ($p<0.05$), which confirms the influence of measured factors on soil macrofaunal community (Fig. 5.3.5).

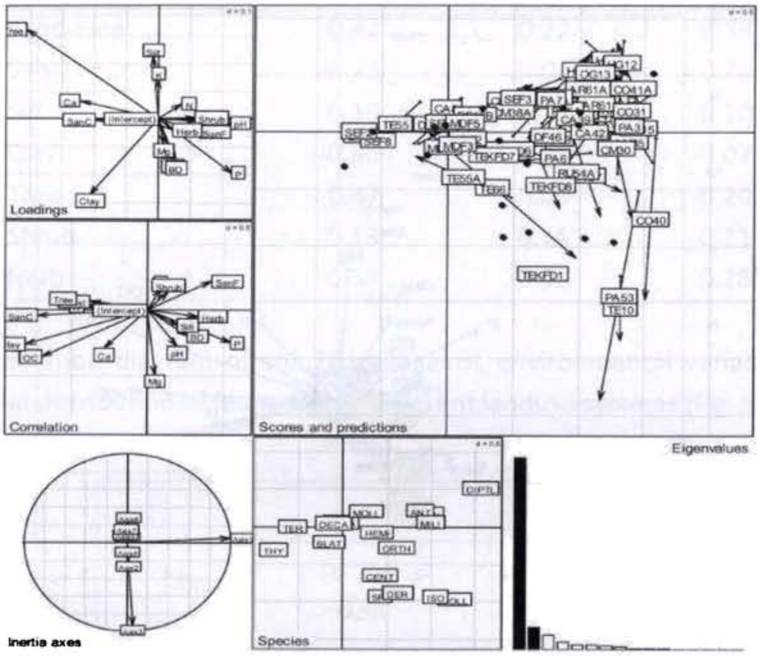

Fig. 5.3.4. CCA compound graphics, which shows environmental variable loadings and correlations (top and middle left), projection of the axes of the species analysis (correspondence analysis) into CCA (lower left), species scores (bottom middle), eigenvalue bar chart (bottom right), A biplot of site scores superimposed with their predictions by environmental variables(main graph). Arrow represents prediction of the sites by regression on environmental variables.

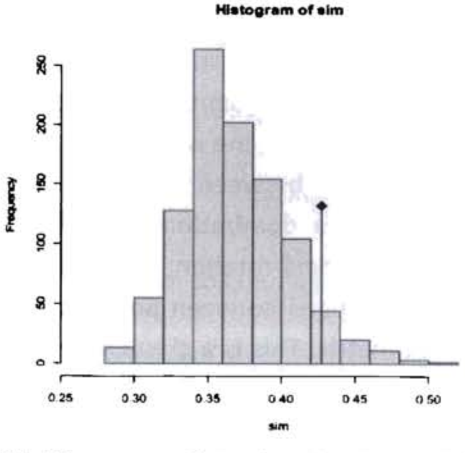

Fig. 5.3.5.Plots of PROTEST. Histogram of simulated value and observed value (vertical line)

In summary CCA ordination diagram (Figs. 5.3.3 a,b) shows that when arrow refers to "P" (Phosphorous), and considering the position of each species, gives an indication of which species occur largely in the phosphorous rich site, which species occur in the phosphorous poor sites, and which species occur in sites with intermediate values for phosphorous. So, the ordination diagram constructed (Fig. 5.3.3a,b) can be explained accordingly: each arrow determines a 'direction' or 'axis' in the diagram, obtained by extending the arrow in both directions. From each species point, a perpendicular line is drawn to this axis. The arrow for "P" has been extended and perpendiculars have been dropped to this axis species points. The endpoints indicate the relative positions of the centre's of the species distributions along the "P" axis or, more precisely, they indicate in an approximate way, the relative value of the weighted average of each species with respect to phosphorous. From Fig. 5.3.3a, it is inferred that Thysanura showed the lowest weighted average with respect to phosphorous; Termite showed the second lowest value, and so on to Coleoptera larva, which is inferred to have the highest weighted average. This interpretation of the ordination diagram is unambiguous. The species, whose distribution is most constrained by phosphorous is on the top-right hand corner of the diagram, while others at the opposite direction.

5.3.4. Model Building

CCA ordination uses all the variables simultaneously to interpret the variation. All the variables may not be equally important, and it is not necessary to consider all variables and it is very popular to perform constrained ordination using all available constraints simultaneously. Increasing the number of constraints means relaxing constraints: the ordination becomes more similar to the unconstrained one. In constrained ordination, it is better to reduce the number of constraints to just a few, say three to five.

By considering these facts, a model building procedure was employed to find out important variable, which may be good enough to predict the soil fauna composition. For this purpose, automatic model building with forward selection was used. Akaike's Information Criterion (AIC) was used for model selection. The model starts with the entire predictor variable and added each variable and in a second step removed each variable (forward and backward selection). If the model choice was valid, all included variables should be significant, and all excluded variables should be insignificant.

The procedure starts by including all the variables (full model), have AIC value 234.15. In the final model (reduced model,) five variables remained (AIC value 212.8). They are pH, phosphorous, calcium, clay and sand content of soil (Table 5.3.4).

Table 5.3.4. Selected variables for model

Variable	Df	AIC	F	N.Perm	Pr(>F)
P	1	213.06	2.07	199	0.090 .
pH	1	213.09	2.10	199	0.040 *
Ca	1	213.43	2.42	199	0.020 *
Clay	1	215.13	4.05	199	0.005 **
Sand	1	215.27	4.18	199	0.005 **

0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

One problem with model building is that constraining variables are not independent, some time they are correlated. Any one of the correlated variables can be explained with other variables. Such variables are redundant ("expendable") when they are with other variables, but they may be the best variables along and prevent other variables to enter the model. A statistical tool describing this is called variance inflation factor (VIF) which is 1 for completely independent variables, and values above 10 or 20 are regarded as highly multicollinear (dependent on others).

A common rule of thumb is that VIF >10 indicate that a variable is strongly dependent on others and does not have independent information. On the other hand, it may not be the variable that should be removed, but alternatively some other variables may be removed. It is clear that (Table 5.3.5a) coarse sand is highly multicollinear, while Mg is least. VIF value for variables selected for model (Table 5.3.5b) shows that clay content is highly multicollinear.

Table 5.3.5a. VIF of different parameters

pH	OC	N	P	K	Ca	Mg	Moist
2.087	8.168	1.570	1.83	2.35	5.67	1.20	7.01
BD	**SanF**	**SanC**	**Silt**	**Clay**	**Tree**	**Shrub**	**Herb**
3.18	2.95	9.25	6.00	8.74	6.94	1.29	2.86

Table 5.3.5b. VIF of different parameters in model

Clay	P	SanC	Ca	pH
2.266	1.229	2.208	1.483	1.165

Thus from the model it was deducted that soil particles (Clay and sand), soil chemical parameters (Ca, P and pH) were appropriate to predict the soil fauna spatial distribution.

5.3.4.1. Testing the significance of model

The model was built by permutation, or shuffling the data into random order. Anova test is used to test the significance of the constrained model (Table 5.3.6), which is significant.

Table 5.3.6. ANOVA result of model statistics

	Df	Chisq	F	N.Perm	Pr(>F)
Model	5	0.55	7.41	199	0.005 **
Residual	54	0.79			

0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

The Model refers to the constrained component, and residual to the unconstrained component of the ordination, Chisq is the corresponding inertia, and Df the corresponding rank. The test statistic F, or more correctly "pseudo-F" is defined as their ratio. Do not pay attention to its numeric values or to the numbers of degrees of freedom, since this "pseudo-F" has nothing to do with the real F, and the only way to assess its "significance" is permutation. In simple models like the one studied here we could directly use inertia in testing, but the "pseudo-F" is needed in more complicated model including "partialled" terms.

All terms are compared against the same residuals, and there is no heuristic for the number permutations. The test is sequential, and the order of terms will influence the results, unless the terms are uncorrelated. In this case the same number of permutations will be used for all terms. The sum of test statistics (Chisq) for terms is the same as the model test statistic in the overall test. "Type III" tests analyze the marginal effects when each term is eliminated from the model containing all other terms (Table 5.3.7)

The marginal effects are independent of the order of the terms, but correlated terms will get higher ("worse") P-values. Now the sum of test statistics is not equal to the model test statistic in the overall test, unless the terms are uncorrelated. Finally the significance of axis was tested, the result of which shows that CCA axis I is significant (Table 5.3.8).

Table 5.3.7. Result of marginal analysis

	Df	Chisq	F	N.Perm	Pr(>F)
Clay	1	0.06	4.05	199	0.005 **
P	1	0.03	2.07	499	0.064 ·
Sand	1	0.06	4.18	199	0.005 **
Ca	1	0.04	2.42	499	0.032 *
pH	1	0.03	2.10	499	0.050 *
Residual	54	0.80			

0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

Table 5.3.8. ANOVA result test of significance of CCA axes

	Df	Chisq	F	N.Perm	Pr(>F)
CCA1	1	0.49	33.58	199	0.005 **
CCA2	1	0.02	1.58	99	0.86
CCA3	1	0.01	1.01	99	0.91
CCA4	1	0.01	0.61	99	0.99
CCA5	1	0.00	0.27	99	1
Residual	54	0.79			

0 '***' 0.001 '**' 0.01 '*' 0.05 '.'

5.3.5. Interpretation of Constraints

Qualitative interpretation of the ordination is possible by using the ecological knowledge of the study site or ecological knowledge on species. But ordinations like CCA, environmental variables are used to interpret the ordination by using all the available variables. But model building gave much flexibility to find out the most important variables among the all variables. If the environmental variables are overlaid in the ordination diagram, it is possible to check the linearity of relationship.

In an ordination diagram, arrow indicates the direction of the most rapid change in the environmental variables (Fig. 5.3.3), which is called direction of the gradient. The length of the arrow indicates the correlation between ordination and environmental variables often called strength of the gradient. This method is called vector fitting which assumes a linear relationship between ordination and environmental variables. In general, due to interdependence nature, it is difficult to expect perfect linear relationship, if we fit the surface of environmental variables to the ordination (Fig. 5.3.6),five variables are surface fitted on the sites, derived from model selection.

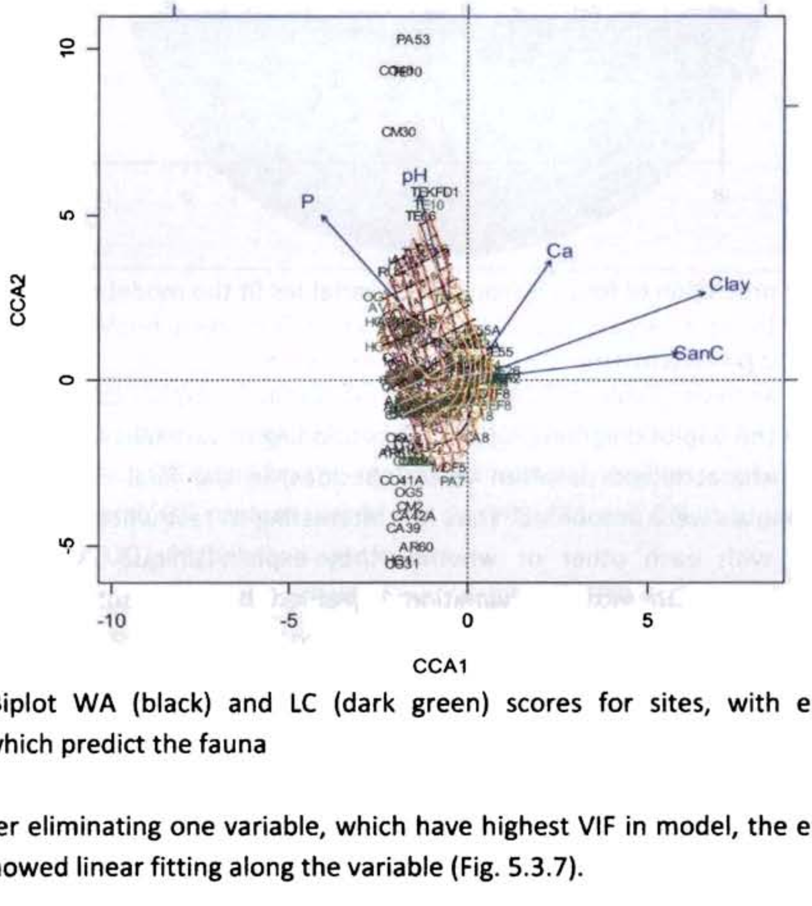

Fig. 5.3.6.Biplot WA (black) and LC (dark green) scores for sites, with environmental variables, which predict the fauna

After eliminating one variable, which have highest VIF in model, the environmental variables showed linear fitting along the variable (Fig. 5.3.7).

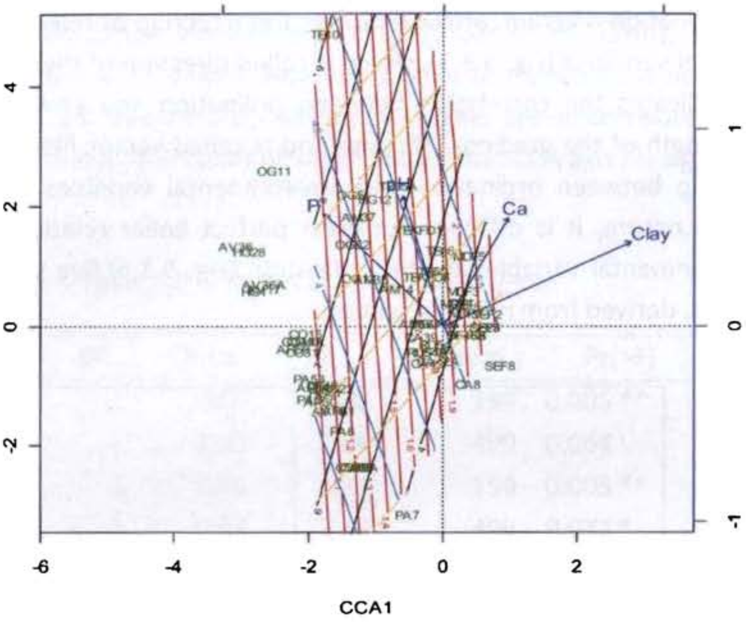

Fig. 5.3.7.Linear prediction of four environmental variables fit the model to the LC scores

5.3.6.Variance partitioning

In CCA analysis (Table 5.3.2A), the overall variance explained by the predictive variables and in the bi-plot diagram (Fig. 5.3.3) partitioning of variables into soil parameters and vegetation characteristics is often visible. Besides, in the final model, none of the vegetation attributes were accounted. Thus it is interesting to test whether the two groups are redundant with each other or whether they explain unique aspects of species composition. In order to find out variation explained by each set of variables (soil parameters and vegetation parameters) variance partitioning was conducted.

Result of the variance partitioning shows that soil parameters have strong control over soil fauna, which also supports the significance of the model. In the model building also, only soil parameters were entered. Variance partitioning shows that (Fig. 5.3.8) soil variables have strong control over soil fauna, which explains 49 per cent of the total variance, while vegetation parameters explains 14 per cent of the total variance. Only 46 per cent of the variation remains unexplained by both of these variables.

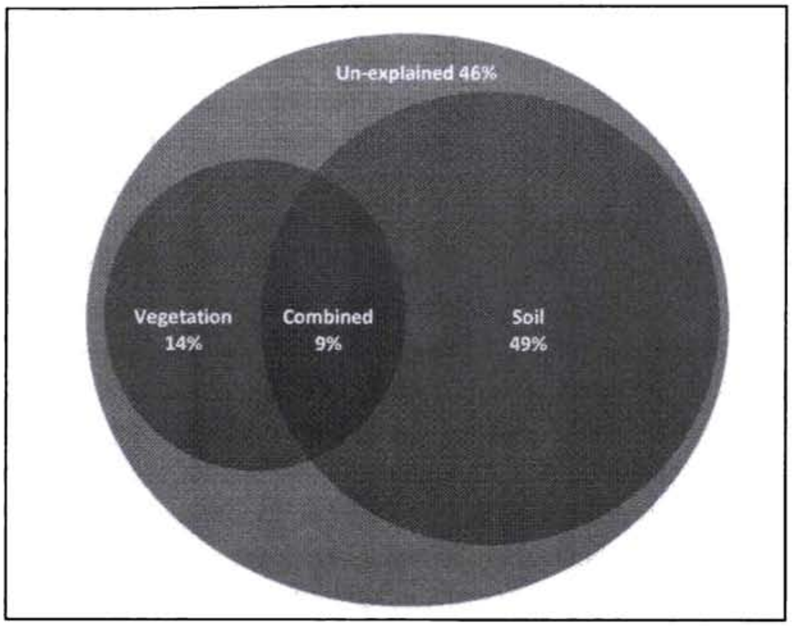

Fig. 5.3.8. Venn diagram showing variance explained by each set of variables

5.3.9. Discussion

Highest moisture content (33.8%) and relatively high OC (2.27%) was observed in SEF. Relatively higher OC could be the reason for relatively higher moisture content in the forest soil. In general, OC content was low in PA, HG, CM and OG. It is generally observed that in plantations OC is higher than agroforests.

Total nitrogen content, as cited above, was low in the study area. This may due to the uptake of plants during the growing period. Phosphorous content was also low in many landuse systems studied, which also urge for nutrient enrichment of these landuse systems. This was also true in the case of potassium. Significantly high Ca content was observed in MDF and DF, which may be due to nutrient release from litter degradation. Mg content was also high in MDF.

It was quite natural that annual cropping systems (PA) lack trees and shrubs, while herb density was moderately high. Highest tree density was observed in SEF, moderate density of tree was also observed in agroforests than plantations. But shrub density showed reverse pattern. As a general rule, agroforests have mixed tree species, while plantations are mainly monoculture in nature. This could be the reason for high tree density in agroforests, probably the same case with herbs also.

In general, the soil of the study area showed that the landuse changes have distinct impact over the soil characteristics. The high soil moisture content and organic carbon content of forest ecosystems may be due to high litter accumulation and degradation of litter. In agroforests and plantations, nutrient content was reduced compared to rest of the landuse types. But some plantations showed comparatively high organic content.

Most of the land owners used inorganic or organic fertilizer as well as pesticides in plantations, agroforestry systems and annual crop fields (Table 5.3.1). They also used green manure in all the agroforestry systems. On the other hand, none of the monoculture plantations except coconut plantation received green manure. Compost and green manure were applied at higher rates in agroforestry systems compared to annual crops. Land owners applied both inorganic fertilizers and compost in monoculture plantations of areca nut, coconut and rubber, but not to cashew and teak. Almost all land owners applied pesticides (mainly herbicides) in rubber plantations. The majority (67-75%) of land owners also applied pesticides in annual crops and some agroforestry systems such as arecanut mixed with annual crops and coconut mixed with perennial crops. Pesticide application was higher in RU and PA, in the former it was in the form of weedicide, but in the latter case, other types of chemicals like fungicide, insecticide etc., were common. Generally, land owners do not apply pesticides in CA and TE. Usually quantity of organic fertilizers used was large compared to inorganic fertilizers. In annual cropping system, inorganic fertilizers were used in much greater quantity than organic fertilizer. Green leaf manure application was also common in agroforests and plantations.

In multivariate ordination techniques, the measured environmental variables relate strongly to the first few ordination axes, they can "account for" (*i.e.*, they are sufficient to predict) the main part of the variation in the species composition. If the environmental variables do not relate strongly to the first few axes, they cannot account for the main part of the variation, but they may still account for some of the remaining variation which may be substantial. These limitations can only be overcome by methods of direct gradient analysis, in which species occurrences are related directly to environmental variables (Gauch, 1982a,b).

The analysis shows that the measured environmental variables have strong control over soil fauna. CCA is a technique that selects the linear combination of environmental variables that maximize the dispersion of species scores. CCA chooses the best weights for the environmental variable which gives the first CCA axis. In each iteration cycle, multiple regression is carried out of the site scores. After several iterations, resulting score constitute the axis of CCA which give canonical coefficient and multiple correlations obtained through is called species environment correlation. Correlation value is high in the analysis, which is a measure of association between species and environment. Eigenvalues gave better information on species-environment relation, because axes with small eigenvalue may give high species-environment correlation. Here eigenvalue (Table 5.3.2B) explains the variation equally well. The randomization test showed that there was accountable association between two data sets. This indicate that soil fauna and environmental variables are correlated and the correlation is significant ($p<0.05$).

CCA simultaneously use all the input variables to plot the spatial distribution of species in biplot. But all the predictor variables may not require all time, because of difficulty to study all the variables within a limited time. WA scores and LC scores and their relation is important in studying the species-environment relation, and increasing number of constraining variables cause ordination is less meaningful (Oksanen, 2009a, b).

The model selection procedure employed to find out most important variables yielded a very promising result. Out of the 16 variables used in CCA (full model), 5 variables found most important (reduced model), which was statistically significant too ($p<0.001$). The reduced model included phosphorous, pH, calcium, clay and sand content of the soil. The model variables were selected based on AIC and in the final model highest AIC value was 215.27 (Sand) and lowest value was 213.06 (P). The VIF statistic showed that variables were not much multicollinear, and highest VIF value in full model was observed in coarse sand content lowest for Mg.

CCA produce triplot diagram showing species, site and environmental variables, from this triplot, direction and strength of the gradient could be inferred. Besides it is possible to surface fit the environmental variables in the ordination diagram which give more precise meaning to the interpretation. If the response is really linear and vectors are appropriate, the fitted surface is a plane whose gradient is parallel to the arrow, and the fitted contours are equally spaced parallel lines perpendicular to the arrow. A curve instead of parallel lines arrow was obtained, and if removing one variable (sand), surface fittings seem parallel to the vector. This may be due to either multicollinearity of the variable, or it may be work in three dimension.

Variance partitioning shows that soil parameters have strong influence on soil fauna than vegetation. This may be due to that in managed systems above ground vegetation is 'planned biodiversity'. Major portion of variance is explained by soil parameters (49%). Only 46 per cent of variation remains unexplained.

Chapter 6

GENERAL DISCUSSION

CHAPTER 6: General Discussion

Soil habitat is an important component of terrestrial ecosystem; it contains one of the most diverse assemblages of living organisms known to us. The issues relating to belowground biodiversity (BGBD) are the same as those related to its counterpart aboveground (AGBD). The concealed nature of belowground biodiversity, however, has led less attention being paid to it in the past; especially there is an absence of 'charismatic' species that draw attention.

As mentioned, due to the sheer diversity of soil and soil living organisms, soil biodiversity studies pose many practical difficulties in sampling, identification and interpretation of results. Besides, soil biodiversity is strongly scale dependent, the relation between 'landuse' and 'biodiversity' is much more complex. Losses of natural and semi-natural forests, mostly to agriculture, are a significant concern for biodiversity. On the contrary, the area of intensively managed and human dominated 'working landscapes' are increasing; there is much debate on the implications for biodiversity conservation in these areas. These facts add multiple dimensions to soil biodiversity studies. A 'soil ecosystems approach' with interpretation of biodiversity in terms of soil biological, physical, chemical as well as socio-economic aspect is an ideal solution under such conditions.

Characterization of soil faunal biodiversity with shifting landuse has great significance. Landuse changes (the purpose for and the manner in which biophysical attributes of the earth's surface and immediate subsurface are manipulated) have great impact on biodiversity. Land-use change is projected to have the largest global impact on biodiversity within 100 years (Sala *et al.*, 2000; Chapin *et al.*, 2000). Though area under forest is reducing with time, biodiversity in managed landscapes gain more attention of conservation value, because as much as 90 per cent of the biodiversity resources in the tropics are located in human dominated or working landscapes (Nair, 2008). Landuse intensification witness extreme events like continuous utilization of same land for years-the permanent agriculture (Giller *et al.*, 1997) at one end to low intensified agroforestry systems with multipurpose tree crops (MPT) at the other end, which have vital role in the tropical biodiversity conservation (Nair, 2008).

Habitat heterogeneity as a function of crop diversification (for eg: agroforestry systems in the tropics) play an important role in increasing the diversity of food resources and environmental conditions for the soil biota while use of pesticides, frequent and/or deep tillage, lack of adequate organic matter management and physical degradation (erosion, compaction), contamination and pollution etc., play a negative role. From the moment a natural system is modified, major changes occur to the soil environment and to the community present there. The intensity of the change induced and the ability of the various organisms to adapt to these changes will determine the ultimate community present after the perturbation.

During the study, different types of landuse systems with varying land-use intensification were sampled for soil macrofauna. The landuse systems vary in cropping pattern, management, inputs and landuse conversion history. This includes pure agriculture at one end to pristine natural forest at another end. The landuse systems sampled represent major ecosystems of the tropics (agriculture, agroforestry, plantations and forests) which facilitate interpolating the results to a broader scale.

Based on the inventory made on the soil macrofauna, 17 higher taxonomic categories (supra-specific taxa) were identified from the study area. The practice of using higher taxonomic groups in environmental monitoring has been developed as an effective tool in the study. As opined by Duelli and Obrist (2003), this tactics facilitated sampling of a large taxonomic spectrum (soil macrofauna) in a large area. Data generated show how the different landuse intensification gradient affects soil macrofauna. Though there was no statistically significant difference in richness of supra-specific taxa across the habitat, the mean number of taxa and the total number of individuals (abundance) was increasing from agricultural systems to natural forest. The result indicated that richness and abundance of soil fauna increased with increasing heterogeneity of the systems and decreasing disturbances. There was ample evidence for spatial patterns affecting the distribution of soil fauna. Fahrig (2003) reviewed the effect of habitat fragmentation on biodiversity and concluded that, fragmentation and habitat loss have increased negative effect on biodiversity. Similar type of observation was also made by Rossi and Blanchart (2005). Changes in landuse affect soil macrofauna (Perner and Malt, 2003). Though there was bias in opinion; habitat heterogeneity affects the abundance and diversity of organisms (Gonzáez-Megias *et al.*, 2007). The present study indicates that habitat modification have profound negative effect on soil macrofaunal diversity and abundance.

Detailed study on diversity of "representative taxonomic group" (ecosystem engineers) also showed similar pattern like higher taxonomic orders. During the study, 27 species of ants, seven species of earthworms and six species of termites were recorded. Though comparison of total number of species in each group (community composition) is not meaningful, ant diversity was high when compared to the other two groups. Further analysis reveals that landuse characteristics and related parameters were the main factors which influenced the diversity.

While looking the habitat-wise distribution of these groups, there was a gradual increase in the number of species from intensively managed agricultural systems to less intensively managed agroforestry systems and forests. A popular assumption is that anthropogenic interference results in loss of biological diversity and the most frequently cited example is of agricultural intensification directly resulting in a reduction in biodiversity (Giller *et al.*, 1997). The data also support this hypothesis that land intensification has negative impact on soil macrofauna. Less intensively managed agroforestry systems have more number of ant species than in the forests. Termites and earthworms are more diverse in forest ecosystems. This trend can be explained, because the former group is more mobile than the latter and can easily be colonized in post-disturbed lands. While considering soil nutrient and other parameters, forest soil is more suitable for soft bodied animals like earthworms and termites. Besides, understory vegetation provide excellent niche for ants, while colonization and subsistence of earthworms and termites depend more on soil quality and intensity of disturbance. Land preparation and clearance prevent successful establishment of underground nest by termites and reduce food availability (Black and Okwakol, 1997). In most of the landuse systems studied, such activities are frequent. Earthworm diversity was also confined to natural systems than rest of the habitats. In natural systems, four species were recorded, while in the agriculture system only one species was recorded. Earthworm biodiversity often modified, when natural systems were replaced by agroecosystems, which affects the taxonomic and functional composition (Fragoso *et al.*, 1997). Bhadauria and Ramakrishnan (1991) reported that upon disturbance, native species was replaced by exotic species and succession never resulted in the restoration of native community. Bano and Kale (1991) reported that native species was adapting to agroecosystems and endogeic species is increasing. Similar type of observation was made by Blanchart and Julka (1997) that the disturbed landuse systems have more endogeic as well as peregrine exotic species. In a recent study (Suthar, 2009) from northern part of India reported that, anthropogenic pressure has more influence on earthworm communities. In this study, the total number of earthworm species was just half collected from integrated and organic farming system, indicating the possibility of earthworms as a bio-indicator of good land management. Studies reveal that, exotic species like *P.corethrurus* can reach a maximum density in disturbed areas (Fragoso *et al.*, 1997). The present study also showed a similar trend, though the total number of species was less.

With respect to individual landuse systems, species richness varied across landuse systems, and lowest richness was observed in coconut monoculture, where fertilizer and pesticide inputs were frequently applied. Highest species richness was observed in landuse systems with minimum disturbances (SEF and MDF). Abundance was also found to be varied with management and disturbance regimes. Increased abundance of species/community itself is an indication of ecosystem sustainability and studies suggest that species abundance model can be used to detect habitat disturbances (Hill and Hamer, 1998).

In the present study, soil macrofauna showed patchy distribution throughout the landuse systems sampled. As opined by Sileshi and Mafongoya (2007), many group of soil fauna showed over dispersion with excess zeros (zero inflation). Out of the many statistical models used, NBD was found to fit well for earthworm, ant and beetles and for termites ZINB was found suitable. Agriculture systems have low abundance of earthworm. Ants, termites, beetles, centipedes, orthoptera and spiders were more abundant in forest ecosystems. Similar observation was also made by many workers (Blanchart and Julka, 1997; Rossi and Blanchart, 2005). As total species richness is an indication, spatial distribution of species across different sites gave a good indication of ability of species to compete and interact (Coleman and Whitman, 2005).

Spatial pattern of soil biota and variability of their densities often regarded as a 'noise' (Ettema and Wardle, 2002). There are many reasons such as resource partitioning, environmental factors, disturbance regimes and intrinsic properties which shape the magnitude of the distribution. Most simply, spatial heterogeneity in soil resources results in microhabitat diversity, which can promote species coexistence through greater resource partitioning. Canonical correspondence analysis was chosen to test the association of soil macrofauna with habitat characteristics. The reason for selecting CCA was that it performs well even if the data is not ideal, with skewed distribution of species, with high 'noise' level, with complex sampling design, and also with non-orthogonal and collinear variables (Palmer, 1993). Besides, it will not create artificial "arch effect" and "tongue effect". The result showed that, CCA performed well in such a situation, and it accounted for greater part of variation (first three axes accounts for 89 per cent of the total variation).

Search for 'variable of importance' (model building) was promising, identified the most important factors shape the soil faunal community. It is meaningless if we consider all the variables, because it is time consuming and questions the model building itself. Interpretation of result is easy only if there are minimum variables, which can be extended to future sampling. In CCA, all the factors would be used for interpreting the variation (full model). In model building procedure applied here, factors which are more influential are selected by using a forward and backward procedure and final model (reduced model) is selected based on AIC and multicollinearity among the factors. The final model eliminates some variables and remains a few variables. Among 16 variables used in CCA, five variables (phosphorous, pH, calcium, clay and sand content) were remained in the final model and the selected model was significant (p<0.005). Based on this, it was inferred that these parameters are more importance than rest.

It will be more meaningful, if information on total biodiversity of a habitat is available for evaluation of the habitat. It is not pragmatic due to technical difficulties. So it may be better to find out a proxy (species or a community) which can serve as single value for the entire spectrum of biodiversity (Duelli, 1997). To validate the effectiveness of 'ecosystem engineers' (ants, earthworms and termites) as a proxy, correlation between the mean number of taxa (higher taxonomic order recorded from each habitat) and mean number of species of ants, termites and earthworms was tested separately. The result (Fig. 6.1) shows positive correlation. Correlation between number of termite species and higher taxa (0.98) and those of earthworm and higher taxa (0.97) found significant, while with ants and higher taxa (0.66) found positive, but not significant. This information was crucial and extends the possibility of termite and earthworms as a surrogate for the diversity of the entire soil macrofauna.

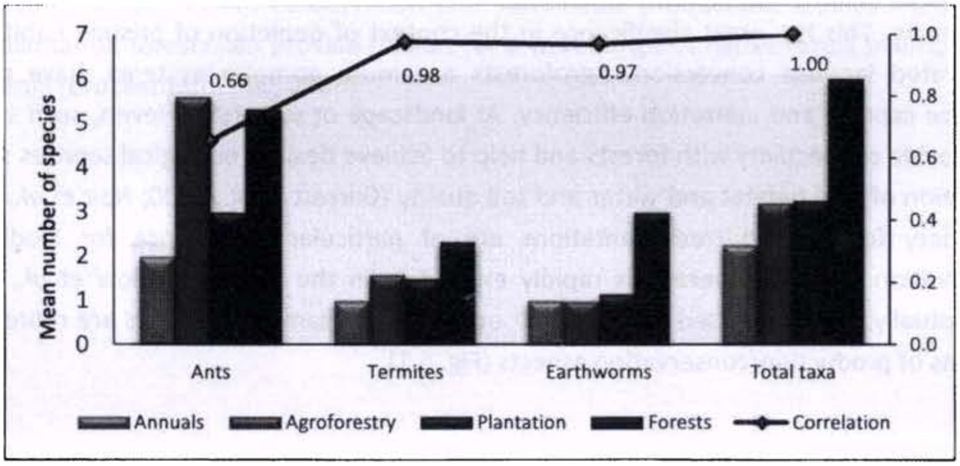

Fig. 6.1. Correlation between mean numbers of higher taxa with ecosystem engineers across different habitat studied

Inventorying entire macrofaunal components in the soil is time consuming as well as expensive with technical problems of getting the identity at species level. Classifying them to coarse taxonomic resolution is more or less easy. On the contrary, sampling and identification of ants, termites and earthworms are comparatively easy. These groups are more or less well studied, taxonomically interesting and abundant and have distinct ecology and trophic requirements. They also can serve as sensitive indicator of habitat perturbations and anthropogenic disturbances. They are often designated as ecosystem engineers due to their ability to modulate other organisms living in soil. Thus, if information on these groups is available, it may serve as base data on the belowground biodiversity, either in local or at landscape level.

The structural heterogeneity produced by plants and associated changes in abiotic gradients can shape the size and heterogeneity of the habitat (Dauber *et al.*, 2005; Eggleton *et al.*, 2005). Though, habitat heterogeneity contributes to maintain diversity, evidence for influence of local scale heterogeneity (*e.g.*, plot level) on soil invertebrate community is less known (Vanbergen *et al.*, 2005). Their studies indicate that soil fauna richness in turn was more in landscape with a mosaic of habitats. Individual fauna may be correlated with local scale habitat variables; overall habitat structure provides, as in the present study, a good refuge for soil fauna.

Agroforestry and monoculture plantations (to some extend) would be better areas for conservation of not only of aboveground biodiversity, but also of belowground biodiversity. This has great significance in the context of depletion of pristine habitat and accelerated landuse conversion. Agroforests are more complex systems, have greater resource capture and utilization efficiency. At landscape or watershed levels, such systems can provide connectivity with forests and help to achieve desired ecological services such as protection of wild habitat and water and soil quality (Garrett *et al.*, 2000; Nair *et al.*, 2008). Secondary forests and tree plantations are of particular importance for biodiversity conservation as their coverage is rapidly expanding in the tropics (Barlow *et al.*, 2007). Conceptually, and also based on the result obtained, the sampled habitats are represented in terms of production/conservation aspects (Fig. 6.1).

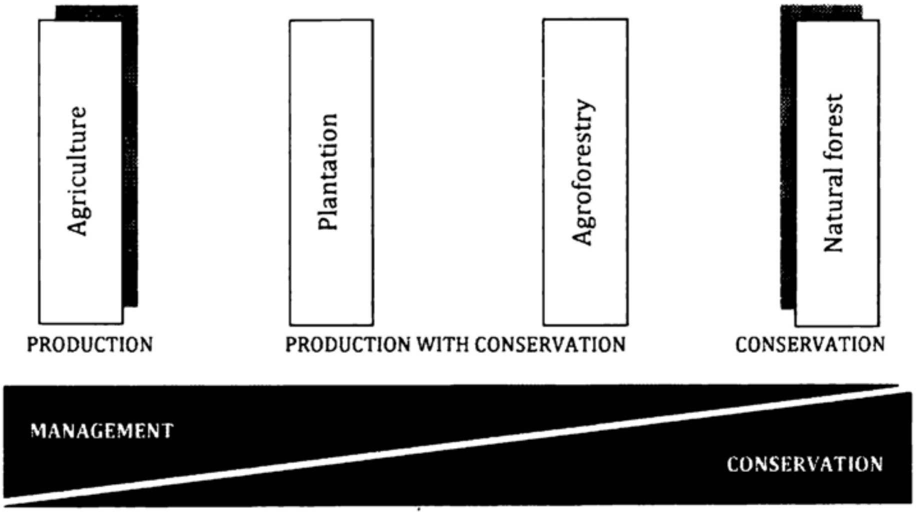

Fig. 6.1. Categorization of selected habitat for biodiversity conservation/production value

Agriculture systems aim mainly for production; natural forest aims conservation and protection of wild habitats and biodiversity. Agroforestry and plantations are placed intermediate. Multi-purpose tree crops in the agroforestry and less management intensity enhance its value in both conservation and sustainable production. Studies indicate that that plantation forests can provide habitat for a wide range of native forest plants, animals and fungi (Brockerhoff et al., 2008).

Chapter 7

CONCLUSIONS

CHAPTER 7: Conclusions

The Nilgiri Biosphere Reserve has unique features such as topography, climate, vegetation and soil type. The landscapes are mosaic and landuse systems are highly dynamic in nature. The heterogeneous nature of habitat provided an excellent platform for studying the spatial pattern and dynamics of soil biotic community. Simultaneous availability of different disturbance gradients extended the possibility of 'space-for-time substitution' studies. The results also are a reflection of temporal change in the soil macrofaunal community along a landuse intensification 'gradient'.

For rapid biodiversity inventory, higher taxonomic orders or species surrogacy is generally considered as a good tool, substantially reducing the time and cost factors. The same technique was espoused here, the grouping was good enough to characterize the spatial pattern of soil macrofauna to land intensification gradient. Thus supra-specific taxa (morphospecies) is a good surrogate for rapid biodiversity assessment.

Soil communities like ants, earthworms and termites can very well be used as good candidates for monitoring landuse perturbations. These groups being well studied, abundant and sensitive to habitat changes, proved to be good indicators of landuse modification/transformation.

As seen in the present study, excess zeros and over-dispersion are characteristic of soil animal count data, which violate the assumptions of standard statistical tests. Despite, commonly used analyses like non-parametric tests and log-normal least square regression (*i.e.*, ANOVA), fail to accommodate excess zeros. For comparing inter-habitat variation, variation among plot or treatments, standard negative binomial distribution (NBD), zero-inflated Poisson (ZIP) or zero-inflated negative binomial distribution (ZINB) perform better than conventionally used non-parametric test, log normal and Poisson tests. It is concluded that irrelevant interpretation can result in biased estimation of ecological effects, jeopardizing the integrity of the scientific inferences.

Measured environmental variables 'accounted' for great variation in soil macrofauna. Out of the 16 factors studied, only five factors were found to be crucial and were considered as key variables. In future, information on these factors are enough to interpret spatial pattern and dynamics of soil faunal communities, at least in the managed landscapes.

Change in the number of species of soil organisms function as indicators of soil fertility or its exhaustion. Physico-chemical properties of soil including management practices are indicators of the 'health' of soil, and have indirect effect on belowground biodiversity. Maintenance of adequate organic matter, wood remnants, mulching etc., facilitate micro-habitats for a vast array of soil organisms. This can be employs as good strategy for ecosystem recovery, improving soil fertility and ecosystem functions.

The present study proves the hypothesis that anthropogenic disturbance has negative impacts on soil fauna. Native vegetation clearance, habitat loss and fragmentation negatively affected soil macrofauna. Soil quality and soil macrofauna responded positively in consensus with increasing habitat heterogeneity. In general, improper land management practices, intensive agriculture and cropping with high input of inorganic fertilizer and pesticides have negative impact on soil fauna. The observed pattern of soil fauna was strongly correlated with habitat heterogeneity which indicates the importance of tropical homegardens and other multipurpose tree cropping systems and plantations (to some extend) in biodiversity conservation and management.

SUMMARY

Summary

Soil is a crucial and one of the species rich habitats in terrestrial ecosystem. It is complex and heterogeneous, and this belowground environment provides numerous niches to soil fauna concerning microhabitats, microclimatic and soil chemical properties. Some fauna are fairly large, while others are inconspicuous. It has been reported that of the total number of described species, 23 per cent are soil living organisms.

Landuse/land-cover change is recognized as an important driver of biodiversity loss, locally as well as globally. Habitat heterogeneity as a function of crop diversification play an important role in increasing the diversity of food resources and environmental conditions for the soil biota while use of pesticides, frequent and/or deep tillage, lack of adequate organic matter management and physical degradation, contamination and pollution plays a negative role. From the moment a natural system is modified, major changes occur to the soil environment and to the community present there. The intensity of the change induced compared with the original ecosystem and the ability of the various organisms to adapt to these changes will determine the ultimate community present after the perturbation. Hence, the present study was carried out to gather information on the soil macrofaunal biodiversity in the context of rapid landuse changes and intensive land utilization with the following objectives: 1) Document major soil macrofauna (earthworm, termite and ant) in selected agroecosystems and natural forests in the Kerala part of Nilgiri Biosphere Reserve, 2) Analyze the distribution pattern of soil fauna in relation to the landuse systems and 3) Evaluate the impact of edaphic and climatic conditions of the habitat on the diversity and abundance of soil fauna.

The study was conducted in the Kerala part of Nilgiri Biosphere Reserve. The experimental area is located at Vazhikkadavu near Nilambur of Malappuram District. Within this area, detailed study was conducted in the Karakkode micro-watershed (between $11^0 15'$N and $11^0 27'$N; between $76^0 17'$E and $76^0 24'$E). The area was divided into 200 m x 200 m grids and the intersection point of grids were marked using a GPS. In total, 15 different land-use systems could be recognized based on specific practices. These landuse systems fell under four main ecosystems, based on the biophysical conditions and management practices. The agricultural systems consisted of mainly annual crop fields (PA). Agroforestry systems with multi-strata homegardens (HG), polyculture farms (OG), arecanut with annuals (AV), arecanut with perennials (AM) and coconut with perennials (CM). Plantations consisted of monoculture stands of arecanut (AR), coconut (CO), rubber (RU), cashew (CA), teak plantations managed by the Forest Department (TE-KFD) and teak plantations managed by private land owners (TE). The forest systems consisted of degraded forest (DF) moist deciduous forest (MDF) and semi-evergreen forests (SEF).

Soil macrofauna were sampled from all 15 different landuse systems. Standard methods like soil monoliths, line-transect protocol and pit-fall traps were used for sampling the fauna. The entire soil macrofauna were grouped into higher taxonomic groups (supra-specific taxa). Simultaneously, diversity and habitat-wise distribution of three ecologically distinct groups of soil macrofauna (ecosystem engineers) namely, ants, earthworms, and termites were collected. Information was also gathered on physico-chemical properties, biological and management of soil in the landuses and also on the general climatic pattern. Diversity and community composition were analyzed to study the response of each population to landuse intensification. Generalized linear models were employed to analyze the underlying distribution pattern of soil macrofauna across the landuse gradient and canonical correspondence analysis were used to evaluate the impact of environmental factors on soil macrofauna.

Altogether, 17 parataxonomic units (higher taxonomic groups) were identified from the 15 different landuse systems. This includes earthworms (Annelida), termites (Isoptera), ants (Hymenoptera), adult beetles and larvae (Coleoptera), earwigs (Dermaptera), Orthoptera (hoppers, crickets, mole crickets), Hemiptera (bugs, coccides, cicadas etc.), woodlice (Isopoda), centipedes (Chilopods), millipedes (Diplopods), Diptera larvae, Decapods, Mollusca, Blattids, Thysanura and spiders (Arachnida).

The number of highest taxa per monolith significantly varied ($\chi^2 = 79.1$, $P<0.0001$) across ecosystems. The lowest and highest number of taxa was recorded in annual crop fields and forests, respectively. The total number of individuals (all taxa combined) per monolith was significantly higher ($\chi^2 = 195.4$, $P<0.0001$) in forest ecosystems than all other ecosystems. Annual crop fields showed the lowest number of individuals, while agroforests and plantations were comparable, but significantly higher than annual crop fields.

While considering individual landuse systems, richness of supra-specific taxa also showed significant variation ($\chi^2 = 159.1$, $P<0.0001$). The lowest number of taxa was recorded in coconut monoculture, while the highest was in moist deciduous and semi-evergreen forests. Compared to the deciduous and semi-evergreen forests, all other landuse practices had significantly lower number of taxa per monolith.

A total of 27 species of ants under 17 genera and 5 subfamilies were collected during inventory. Of the five subfamilies reported, Myrmicinae was the most diverse with 8 genera and 12 species and subfamily Formicinae with 8 species in 3 genera. Five species were collected under the subfamily Ponerinae, but under Dolichoderinae and Ectatomminae subfamily, only one species each was collected. *Camponotus* was the most diverse genera with six species, followed by *Monomorium* with three species. The foraging species *Myrmicaria brunnea* was recorded from all landuse systems. *Anoplolepis longipes* was the second common species present in six out of 15 landuse studied. Different species of *Camponotus* also showed wide spread distribution and was reported from seven landuse systems. Of the four main ecosystems studied, agroforestry systems showed highest diversity of ants. Forests, plantations and annual crops came second, third and fourth position, respectively. While considering individual landuse systems, polyculture farms ranked first with 12 species followed by semievergreen forest and homegarden with seven species and moist deciduous forest with five species.

Ants were collected from all landuse systems and from all plots, but showed a non-uniform distribution. Highest numerical abundance (248 individual m^{-2}) was observed in plot 8 in semievergreen forest, followed by plot 41 of homegarden (180 individual m^{-2}). Least abundance (4 individual m^{-2}) was observed in plot 31 of coconut and in plot 55 of private teak plantation. Abundance of ants also varied among the plots of a given landuse system.

A total of seven species of earthworms, under five families were recorded and among these, *Pontoscolex corethrurus* (Glossoscolecidae) showed wide spread distribution. Maximum diversity of earthworms was recorded in semi-evergreen forest, with four species, followed by moist deciduous forest, with three species. The peregrine species, *P. corethrurus* was the most abundant species in crop based systems and was also collected from semi-evergreen forest. *Megascolex* sp. and *Drawida* sp.B were recorded exclusively from forest ecosystems-both from semi-evergreen forest and moist deciduous forest, while *Glyphidrilus* sp., which is a semi-aquatic inhabitant, was recorded from the coconut based landuse systems.

Looking at the functional-ecological-categories of earthworms, *Megascolex* sp. was the only epigeic species, which was recorded from forest ecosystems. *Drawida* sp. and *Lampito mauritii* are anecic species. Endogeic species, *P. corethrurus* was the abundant species, which accounted for >90 per cent of the total collection.

The highest numerical abundance (639 individuals m^{-2}) and lowest numerical abundance (four individuals m^{-2}) was observed in coconut mixed with perennial systems, in plot 2 and in plot 30 and 38A respectively, followed by plot 5 of moist deciduous forest (456 individuals m^{-2}).

Termite diversity was poor in the study area, a total of six species of termites, under 5 genera and two families were collected. Among the five genera recorded, *Odontotermes* with two species, and others with a single species each. Forest ecosystems showed maximum diversity of termites with five species. Three species were collected from plantation ecosystems. From agroforestry and annual crops, only one species each were collected. Of the four species collected from semi-evergreen forest and moist deciduous forests, three species were common, while one species was collected exclusively from each landuse type. *Odontotermes obesus* showed wide distribution. Termites were absent in some plots, but in some cases abundance of termites was as high as 9038 individuals m^{-2} as in the case of semi-evergreen forests.

While considering the individual taxa, earthworms were significantly more abundant in agroforests, plantations and forest ecosystems than in annual crop fields. Ants and termites were more abundant in forest ecosystems than all other ecosystems. Millipedes were more abundant in agroforestry than all other ecosystems. Beetles, centipedes, Orthoptera and spiders were more abundant in forest ecosystems than all others. The other macrofaunal groups had more zero counts; hence meaningful comparisons could not be made among ecosystems. The result of PCA showed that, the first three axes accounted of 55 per cent of the total variation. Those landuse systems, which had high overall abundance of most macrofauna *viz.*, teak plantation under Forest Department, teak plantation under private ownership, moist deciduous forest and semi-evergreen forest, are grouped in the upper right panel of the bi-plot.

Data on soil physico-chemical parameters indicated that, nutrient status in most of the managed landuse systems was below standard recommendations. Each landuse type sampled showed a unique feature in management, nutrient status, cropping pattern and vegetation parameters. Most of the land owners used inorganic or organic fertilizer as well as pesticides in plantations, agroforestry systems and annual crop fields.

Measured environmental variables accounted for greater variability in soil fauna, first axis of canonical correspondence analysis accounted for 75 per cent of the total variation. High species-environment correlation was also observed (0.93). This was confirmed by PROTEST, which indicated that soil physico-chemical parameters have strong influence on soil community.

In canonical correspondence analysis, all the measured factors are used to interpret the ordination. Model building is a flexible technique to find out most important variable. Out of 16 factors used in canonical correspondence analysis, five variables were found to be crucial, namely pH, Phosphorous, Calcium, clay and sand content. None of the vegetation attributes (tree, herb and shrub density) were important. Variance partitioning also indicated that soil parameters account for 49 per cent of the variability, while vegetation parameters account for only 14 per cent of variation. Only 46 per cent variation remains unexplained by both these factors.

In summary, richness of ants, termites and earthworms as well as higher taxonomic groups of the entire soil macrofauna increased with increasing heterogeneity of the systems and decreasing disturbances. Soil quality and soil macrofauna responded negatively to landuse intensification and changed positively in consensus with increasing habitat heterogeneity. The results support the growing body of literature that points towards the negative impact of native vegetation clearance, habitat loss and fragmentation on biodiversity. It also supports the hypothesis that anthropogenic disturbance has negative impacts on soil fauna.

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APPENDIX

Table A1. Abundance (individuals in 25 x 25 x 30cm area) of soil fauna from different landuse systems*

	EW	TER	ANT	MILI	CENT	COLA	COLL	DIPTL	SPI	ISO	DECA	MOLL	BLAT	ORTH	DER	HEMI	THY
HG1	9.25	0	1	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0
HG12	2.25	0	3.75	0.5	0	0	0.5	0	0	0	0	0	0	0	0	0	0
HG28	1	0	4.75	0	0.25	0.25	1	0.25	0	0	0	0	0	0.25	0	0	0
HG41	2.5	0.5	11.25	0	0	1	0	0	0	0.25	0	0	0	0	0	0	0
OG5	9.25	1.25	3.75	1.25	0	0	0	0	0	0	0	0	0	0	0.25	0	0
OG11	1.25	0	5	1	0	0	0	0	0	0	0	0	0	0	0.25	0	0
OG13	6.25	0	9.75	0	0	0	0	0	0	0	0	0	0	0	0.25	0	0
OG52	1.25	2.25	9.25	0	0	0.5	0	0	0	0.5	0	0.25	0	0.5	0.25	0	0
AV17	3.75	0	7	0	0	0	0.25	0	0	0.5	0	0	0	0	0	0	0
AV18	4	1.5	3.5	2.25	0	0	0	0	0	0	0	0	0	0.5	0	0	0
AV36	0.5	0	6.25	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0
AV36A	2	0	7.5	4	0	0	0	0	0	0	0	0	0	0	0	0	0
AM14	2.5	0.5	9.5	1.5	0.25	0	1	0	0.75	0	0	0.5	0	0	0	0	0
AM16	9	0	7.5	0	0	0.25	0	0.5	0	1.75	0	0	0	0	0	0	0
AM35	8.5	0.5	3.25	0.75	0.25	0	0.5	0	0	1.5	0	0	0	1	0.5	0	0
AM37	2.25	0.5	3	0.75	0.25	0	0.75	0	0	1.5	0	0	0	0.75	0.5	0	0
CM2	39.39	3.5	5.25	0.75	0.5	3	5.25	0	0	0.75	0.25	0.75	0	0.75	0	0	0
CM30	0.25	0	0.75	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0
CM38	3.5	9.5	0.75	1	0.25	0	0.25	0	0	0	0	0	0	0	0	0	0
CM38A	0.25	9.5	2.75	0.25	0.25	0	0.25	0	0	0	0	0	0	0	0	0	0
AR59	3.75	0	5.25	0	0.25	0	0.5	0	0	0	0	0	0	0	0.25	0	0
AR60	18.75	3.5	0.5	0	0.25	0	0.5	0	0.5	0	0	0.5	0	0	0	0	0
AR61	7.25	0	6.5	0	0	0	1.25	0	0	0	0	0	0	0	0.25	0	0
AR61A	6.25	0	4	0	0	0	0.75	0	0	0	0	0	0	0	0	0	0
CO15	4.5	0	3.5	0	0	0	1.5	0	0	0	0	0	0	0	0	0	0
CO31	22.75	1	0.25	0	0	0	1.5	0	0	0	0	0	0	0	0	0	0
CO40	5	0	3.5	0	0	0	7.75	0	0	0	0	0	0	0	0	0	0
CO41A	4.75	0	4.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0

RU22	7.75	4	4.75	0	0.5	0	0	0	0	0	0	0	0	0	0.75	0	0
RU54	2.5	2.25	0.75	0.5	0	0.25	0.5	0	0.25	0	0	0	0	0	0	0	0
RU54A	3.25	0	3.25	2.5	0	0	1	0	0	2	0	0	0	0.75	0	0	0
RU54B	3.5	2	7.25	1.25	0.75	0	0.75	0	0	1	0	0	0	0.25	0	0	0
CA8	10.5	40.5	5.75	0	0	4	1	0	0	0.25	0	0	0	0	0	0	0
CA39	17.75	0	2.25	0.75	0	1	0.75	0	0.5	0	0	0	0	0	0.5	0	0
CA42	5.5	0	5.25	0	0	0	0.75	0	0	0	0	0	0	0	0.25	0	0
CA42A	11.5	2.5	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TE10	7.75	0	1.25	0	1.25	1	8.75	0	1.75	1	0	0	0	0.5	0.5	0	0
TE66	0.75	0	0.75	0.25	0.75	0.5	0.5	0	0.25	0	0	0	0	0	0.25	0	0
TE55	1	22.75	0.25	0	0	0	0.75	0	0.25	0	0	0	0	0	0	0	0
TE55A	0.75	8.75	1	0.25	0.75	0	0.5	0	0	0	0	0	0	0	0	0	0
PA3	2	0	1.75	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0
PA53	1	1.5	1.25	0.25	0.5	0	3.75	0	0	3.5	0	0	0	0	0.25	0	0
PA7	2.25	0	3.75	0	0.25	0	0	0	0.25	0	0	0	0	0	0.25	0	0
PA6	0.75	2.5	3.25	0	0.75	0.75	0.75	0	0	0	0	0	0	0	0.25	0	0
DF46	0.25	4.25	9.75	0	1	0.25	1	0	0.5	1.5	0	0	0	0	0	0	0
DF26	0.25	203.25	3.5	1	2.5	0	0	0	0	0	0	0	0	0	0	0	0
DF46A	1	8.5	5	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0
DF46B	2.25	5	10	0	1	0	0	0	0	0	0	0	0	0	0	0	0
TEKFD1	5	5.25	1.25	0	0.75	0	3	0	1	1.5	0	0	0	0	1.5	0	0
TEKFD6	5.5	12.5	2.5	0.5	0	0	2.75	0	0	0	0	0	0	0	0	0.75	0
TEKFD7	4	10.5	0.5	0	1.5	0	0.25	0	0	0	0	0	0	0.25	0	0	0
TEKFD8	1.75	1.25	1.75	0	1.25	0	1	0	0	0	0	0	0	0.5	0	0	0
SEF8	8.25	237.5	15.5	0.75	3.5	10	1.5	0	1	1.25	0.5	1.25	1.25	1.25	1.75	0	1.25
SEF2	6	564.9	5.5	0.75	0.75	4.75	0.75	0	1.25	1	0	0.25	0.25	0.75	0.5	0	0.25
SEF4	5.75	18.75	9	0	0.25	0.75	0.25	0	1.25	0.5	0	0.25	0	0.25	0.25	0	0
SEF3	2.5	5.25	9	0.75	0	0.5	0	0	0	0	0	0.25	0.5	0.25	0.25	0.5	0
MDF1	4.75	29.75	3.75	0	1	1	1.25	0	1.25	0	0	0.75	1.5	0.5	0.5	0.5	0
MDF2	7	22	5.75	0	0.75	0	2	0	1	0	0	0.5	0	0.5	0.5	0.25	0
MDF5	28.5	28.5	3	0.25	0.5	0	1	0	0.5	0.5	0	0.5	0	0.75	0	0.5	0
MDF3	7	29.75	6.5	1.25	0.75	0.5	1.75	0	0.5	0.5	0	0.5	0.5	0.25	0.75	0.25	0

*abbreviations are same mentioned elsewhere

Table A2. Significance (P values) of differences between plots within each landuse in the density of soil macrofauna taxa

Landuse	**Earthworm**	**Ants**	**Termites**	**Beetle**
AM	0.098	0.044*	0.548	???
AR	0.049*	0.011*	0.374	???
AV	<0.001*	0.197	???	???
CA	0.243	0.278	0.017*	???
CM	<0.001*	0.231	0.021*	0.496
CO	0.049	0.103	???	???
DF	0.024*	0.101	0.002*	0.089
TE-KFD	0.483	0.175	0.06	???
MDF	<0.001*	0.342	0.821	0.849
HG	0.077	0.038	???	???
OG	0.017*	0.014	???	???
PA	0.779	0.841	???	0.961
RU	0.274	0.054	???	???
SEF	0.045*	0.006*	<0.001*	<0.001*
TE	0.020*	0.797	<0.001*	0.12
Overall	<0.001**	<0.001**	<0.001**	<0.001**

* Significant difference between plots within each land-use practice; ** significant difference between land-use practices
??? Algorithm did not converge under both Poisson and negative binomial distribution assumptions

PA = annual crop fields; HG = homegardens; OG = polyculture farms; AV = Arecanut with annuals; AM = Arecanut with perennials; CM = coconut with perennials; AR = monoculture Arecanut; CO = monoculture coconut; RU = rubber monoculture; CA = cashew monoculture; TE-KFD = teak plantation under Forest Department; TE = teak plantation under private ownership; DF = degraded forest; MDF = moist deciduous forest and SEF = semi-evergreen forests

Table A3. Principal components (PCs), eigenvalues and cumulative proportion of explained variation

Eigenvalues	**% total variance**	**Cumulative eigenvalue**	**Cumulative %**
6.09	35.825	6.09	35.8
1.745	10.264	7.835	46.1
1.466	8.624	9.301	54.7
1.296	7.626	10.597	62.3
1.156	6.8	11.753	69.1
1.127	6.627	12.88	75.8
0.835	4.91	13.715	80.7
0.676	3.976	14.39	84.6
0.565	3.326	14.956	88
0.527	3.103	15.483	91.1
0.452	2.659	15.935	93.7
0.337	1.981	16.272	95.7
0.305	1.796	16.578	97.5
0.191	1.124	16.769	98.6
0.126	0.742	16.895	99.4
0.07	0.414	16.965	99.8
0.035	0.205	17	100

Table A4. Loadings (Eigenvectors) on principal components for the various taxa

	Components									
	1	2	3	4	5	6	7	8	9	10
Coleoptera adult (COLA)	**0.88**	-0.18	0.07	-0.08	-0.16	0.11	0.14	0.05	0.05	0.07
Thysanura (THY)	**0.88**	-0.31	0.04	-0.02	-0.14	0.08	-0.06	-0.11	0.04	-0.01
Decapods (DECA)	**0.84**	-0.13	0.07	-0.30	-0.24	0.18	-0.19	-0.12	0.08	-0.02
Molluscs (MOLL)	**0.83**	0.21	-0.30	-0.22	-0.04	-0.03	-0.02	0.07	-0.01	-0.08
Blattids (BLA)	**0.74**	0.03	-0.41	0.12	0.06	-0.25	-0.10	-0.16	0.03	-0.10
Dermaptera (DER)	**0.72**	0.05	0.12	0.30	0.02	-0.09	-0.25	0.05	-0.32	-0.26
Centipede (CENT)	**0.71**	-0.13	0.07	0.32	-0.09	0.07	-0.04	-0.31	0.20	0.02
Orthoptera (ORTH)	**0.71**	0.19	0.12	-0.20	0.33	0.05	0.10	-0.15	-0.20	0.13
Spider (SPI)	**0.58**	0.40	0.02	0.43	0.08	-0.14	0.14	0.39	0.02	-0.22
Termite (TER)	**0.58**	-0.20	0.07	0.26	0.12	0.11	0.67	0.07	0.05	0.16
Coleoptera larva (COLL)	0.22	**0.68**	0.40	0.09	-0.08	0.09	-0.21	0.11	0.44	0.12
Earthworm (EW)	0.23	**0.55**	0.02	-0.61	-0.24	0.22	0.23	0.09	-0.17	-0.09
Ant (ANT)	0.45	**-0.46**	-0.15	-0.25	0.01	-0.28	-0.21	0.51	0.05	0.27
Isopod (ISO)	0.31	0.11	**0.70**	-0.06	0.37	-0.28	-0.13	-0.08	-0.20	0.23
Hemiptera (HEMI)	0.15	0.48	**-0.63**	-0.04	0.24	-0.34	0.02	-0.18	0.06	0.24
Millipede (MILI)	0.09	-0.21	-0.03	-0.30	0.79	0.28	-0.04	0.05	0.25	-0.28
Diptera larva (DIPTL)	-0.07	-0.14	0.31	-0.33	-0.14	-0.75	0.25	-0.12	0.19	-0.26

Table A5. Soil physico-chemical properties of different landuse systems studied*

	pH	OC	N	P	K	Ca	Mg	Moist	BD	Fine sand	Coarse sand	Silt	Clay	Tree	Shrub	Herb
HG1	6.41	0.73	0.06	7.41	0.19	3.13	0.84	17.53	2.1	53.16	27.13	19.26	0.44	0.14	0.06	100.86
HG12	6.04	0.16	0.7	12.38	0.19	6.53	0.99	16.31	1.97	49.69	26.21	22.27	1.82	0.09	0.09	80.83
HG28	6.35	0.82	0.11	9.55	0.12	5.12	2.2	16.92	2.04	53.16	27.13	19.26	0.44	0.07	0.04	74.10
HG41	5.62	1.24	0.14	5.76	0.3	2.68	0.54	9.36	2.12	53.16	27.13	19.26	0.44	0.06	0.03	78.26
OG5	6.47	1.27	0.06	10.22	0.27	5.07	0.9	26.69	1.69	49.69	26.21	22.27	1.82	0.08	0.09	77.80
OG11	5.71	0.79	0.07	23.19	0.18	3.76	0.63	21.56	1.68	51.43	26.67	20.77	1.13	0.12	0.01	101.07
OG13	6.06	0.85	0.07	9.01	0.14	3.35	0.72	28.79	1.69	50.56	26.44	21.52	1.48	0.09	0.04	99.51
OG52	6.34	0.72	0.03	7.04	0.06	5.62	2	11.19	2.53	50.56	26.44	21.52	1.48	0.12	0.00	41.95
AV17	5.74	0.87	0.05	14.4	0.22	2.91	0.53	13.63	2.2	55.84	28.89	14.83	0.43	0.08	0.02	68.74
AV18	5.55	1.12	0.11	5.63	0.25	1.81	0.49	9.14	2.12	55.84	28.89	14.83	0.43	0.10	0.05	1099.99
AV36	6.15	0.88	0.07	13.99	0.17	3.39	0.81	10.2	2.16	55.84	28.89	14.83	0.43	0.10	0.11	64.21
AV36A	6.04	0.97	0.08	10.78	0.19	3.94	0.97	11.1	2.14	55.84	28.89	14.83	0.43	0.10	0.05	84.21
AM14	6.37	0.99	0.03	3.4	0.13	3.96	1.24	21.84	1.88	49.69	26.21	22.27	1.82	0.04	0.30	133.75
AM6	5.97	1.27	0.03	5.41	0.1	2.55	0.83	32.66	1.47	48.8	27.51	21.57	1.85	0.04	0.58	117.08
AM35	6.64	1.1	0.06	3.97	0.18	1.82	0.68	12.3	2.01	49.5	26.21	22.27	1.85	0.06	0.66	464.40
AM37	5.93	0.52	0.05	15.85	0.03	2.79	1.2	22.85	1.81	49.69	26.1	22.27	1.85	0.11	0.00	33.97
CM2	5.38	0.29	0.02	2.82	0.01	0.98	2.24	15.04	2.21	53.16	27.13	19.26	0.44	0.02	0.06	80.65
CM30	5.38	0.29	0.02	2.82	0.01	0.98	2.24	54.86	2	53.16	27.13	19.26	0.44	0.05	0.13	161.40
CM38	5.38	0.29	0.02	2.82	0.01	0.98	2.24	24.78	1.79	53.16	27.13	19.26	0.44	0.03	0.00	122.75
CM38A	5.38	0.29	0.02	2.82	0.01	0.98	2.24	39.82	2	53.16	27.13	19.26	0.44	0.02	0.07	192.08
AR59	6.13	0.72	0.04	4.35	0.03	3.28	0.47	23.75	1.91	55.84	28.89	14.83	0.43	0.09	0.45	155.62
AR60	5.46	1.22	0.07	8.07	0.11	1.26	0.35	24.14	1.73	88.84	28.89	14.83	0.43	0.17	0.52	106.11
AR61	5.43	1.01	0.14	5.86	0.28	2.78	0.69	25.31	1.82	55.84	28.89	14.83	0.43	0.05	0.30	117.94
AR61A	5.67	0.99	0.08	6.09	0.14	2.44	0.5	24.4	1.82	55.84	28.89	14.83	0.43	0.10	0.42	126.55
CO15	5.92	1.85	0.11	5.87	0.19	5.1	1.09	24.14	2.11	53.16	27.13	19.26	0.44	0.03	0.65	24.28
CO31	5.92	1.59	0.09	5.83	0.23	3.54	0.49	13.76	2.06	53.16	27.13	19.26	0.44	0.02	0.00	100.89
CO14	5.93	1.72	0.1	5.85	0.21	4.32	0.79	18.95	2.09	53.16	27.13	19.26	0.44	0.01	0.22	136.22
CO41A	5.93	1.72	0.1	5.85	0.21	4.32	0.79	18.95	2.09	53.16	27.13	19.26	0.44	0.02	0.23	120.89
RU22	5.51	1.47	0.08	7.16	0.18	2.41	0.58	16.07	2.23	46.2	28.9	23.2	0.6	0.03	0.00	5.92
RU54	5.72	1.35	0.6	5.24	0.13	3.09	0.103	19.7	2.12	49.69	26.21	22.17	1.82	0.06	0.00	91.50
RU54A	5.62	1.41	0.07	6.2	0.15	2.75	0.8	17.89	2.18	47.95	27.56	22.74	1.71	0.04	0.13	247.83
RU54B	5.62	1.41	0.07	6.2	0.15	2.75	0.8	17.89	2.18	47.95	27.576	22.74	1.71	0.04	0.15	95.07

CA8	5.34	2.59	0.11	4.74	2.15	3.5	1.01	13.72	2.2	45.69	30.21	22.74	1.82	0.02	0.08	192.60
CA39	5.86	1.08	0.12	5.53	0.19	2.31	0.6	17.74	1.99	45.96	30.21	22.74	1.82	0.02	0.06	192.60
CA42	5.87	1.93	0.09	3.96	0.11	1.31	0.36	15.73	2.1	54.69	30.21	22.74	1.82	0.02	0.16	140
CA42A	5.69	1.86	0.11	4.74	0.82	2.37	0.66	17.73	2.1	45.69	30.22	22.74	1.82	0.02	0.06	175.07
TE10	6.32	2.71	0.11	23.73	0.35	6.97	1.19	11.08	2.13	45.22	30.22	22.74	2.27	0.07	0.09	120.81
TE66	6.25	1.52	0.06	4.66	0.13	6.05	0.92	10.4	2.02	45.22	30.22	22.74	2.27	0.09	0.07	122.66
TE55	5.57	2.03	0.09	13.66	0.06	2.12	0.9	31.34	2.23	45.22	30.22	22.74	2.27	0.25	2.30	722.15
TE55A	6.05	2.09	0.09	14.02	0.18	5.05	1.01	17.61	2.12	45.22	30.22	22.74	2.27	0.09	0.10	123.66
PA3	5.94	0.41	0.06	3.5	0.09	1.38	6	18.25	2.12	55.84	28.89	14.83	0.43	0.00	0.00	108.17
PA53	5.9	0.8	0.04	4.46	0.05	2.63	0.98	12.53	2.49	55.84	28.89	14.83	0.43	0.00	0.00	124.70
PA7	4.67	1.04	0.05	3.98	1.3	2.03	1.02	18.76	1.96	55.84	28.89	14.83	0.43	0.00	0.00	60.25
PA6	5.5	0.75	0.05	3.98	0.48	2.01	0.87	13.27	2.22	55.84	28.89	14.83	0.43	0.00	0.00	124.60
DF46	5.84	1.68	0	3.35	0.04	3.65	1.31	9.1	2.43	55.84	30.46	24.01	0.43	0.03	0.28	33.33
DF26	5.63	2.05	0.12	1.69	0.04	8.23	2.94	9.1	2.43	43.54	30.46	24.01	1.97	0.03	0.16	0.04
DF26A	5.74	1.86	0.12	2.52	0.04	5.94	2.12	9.1	2.43	43.54	30.46	24.01	1.97	0.04	0.11	268.34
DF26B	5.74	1.86	0.12	2.52	0.05	5.94	2.12	9.1	2.43	43.54	30.46	24.01	1.97	0.03	0.15	100.57
TE-KFD1	6.26	2.38	0.1	3	0.02	10.36	0.97	15.02	2.26	49.69	26.21	22.27	1.82	0.03	0.00	241
TE-KFD6	5.95	1.31	0.08	2.85	0.02	5.03	0.96	17.02	2.12	49.69	26.21	22.27	1.82	0.03	0.00	260
TE-KFD7	6.11	1.85	0.09	2.92	0.04	7.74	0.96	16.02	2.19	49.69	26.21	22.27	1.82	0.02	0.00	378
TE-KFD8	6.11	1.85	0.09	2.92	0.04	7.74	0.96	16.02	2.19	49.69	26.21	22.27	1.82	0.02	0.00	245
SEF8	5.64	2.42	0.18	2.98	0.18	2.76	2.47	40.26	2.16	49.23	31.36	17.03	2.37	0.15	0.04	3.81
SEF2	5.87	2.13	0.14	2.95	0.11	5.25	1.72	27.33	1.49	49.23	31.36	17.03	2.37	0.11	0.00	0.41
SEF4	6.1	2.27	0.16	2.97	0.14	4.01	2.09	33.8	1.38	49.23	31.36	17.03	2.37	0.13	0.27	0.41
SEF3	5.87	2.27	0.16	2.97	0.14	4.01	2.09	33.8	1.38	49.23	31.36	17.03	2.37	0.13	4.38	0.00
MDF1	5.64	2.03	0.09	4.31	0.17	8.24	3.08	14.45	2.29	49.23	26.21	22.27	1.82	0.07	0.45	598
MDF2	5.5	1.98	0.08	4.6	0.32	8.43	2.88	26.06	1.79	49.23	26.21	22.27	1.82	0.04	0.30	432
MDF5	5.62	2.72	0.12	3.91	0.47	12.86	4.36	20.26	2.04	49.23	26.21	22.27	1.82	0.05	0.21	498
MDF3	5.59	2.24	0.09	4.27	0.32	9.84	3.44	20.26	2.04	49.23	26.21	22.27	1.82	0.04	0.21	414

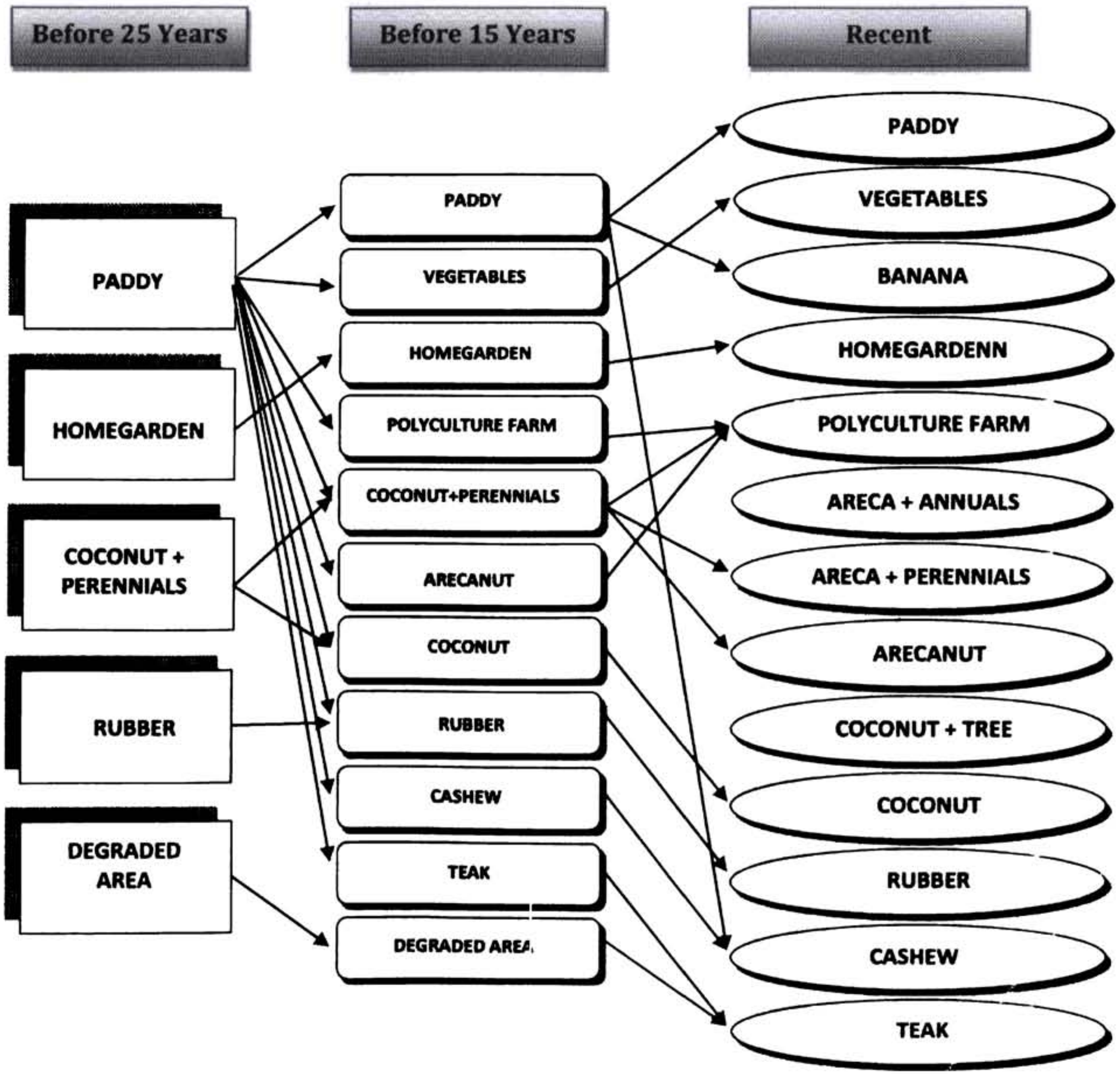
*abbreviations are same mentioned elsewhere

Table A6. Climatic data of the study area

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	RH (%)
January	0.0	0.0	0.2	1.8	0.0	0.0	0.2	0.0	0.2	0.0	57
February	0.0	0.0	0.2	0.1	0.5	0.0	0.0	0.0	0.0	0.0	61
March	0.6	0.0	0.6	0.0	0.0	1.9	0.3	0.2	0.2	0.8	61
April	0.4	1.9	0.5	3.8	4.0	1.8	3.3	2.4	3.1	1.4	69
May	3.8	3.4	11.2	1.6	4.5	4.9	0.9	12.7	1.7	15.6	69
June	17.3	24.1	17.0	15.5	15.8	9.9	13.8	20.3	20.1	17.8	86
July	30.5	24.4	18.4	9.8	17.7	7.6	13.1	14.3	30.9	20.7	92
August	18.7	9.9	9.3	14.4	6.8	10.4	6.3	13.9	11.0	11.6	81
September	6.3	9.4	2.2	6.9	3.0	1.5	1.3	6.4	7.9	16.0	74
October	12.1	10.2	10.0	4.4	8.4	12.1	8.4	8.7	11.3	4.2	80
November	10.4	3.8	1.0	3.2	7.9	2.2	5.3	5.1	7.4	8.3	70
December	1.6	2.3	0.0	3.8	0.6	0.6	0.0	0.0	0.0	0.0	56
Rainy days	136	139	128	126	127	110	108	126	141	130	na
Non-rainy days	230	227	238	240	239	256	258	240	225	236	na
Total rainfall (cm)	312	273	217	200	212	162	162	257	287	293	na

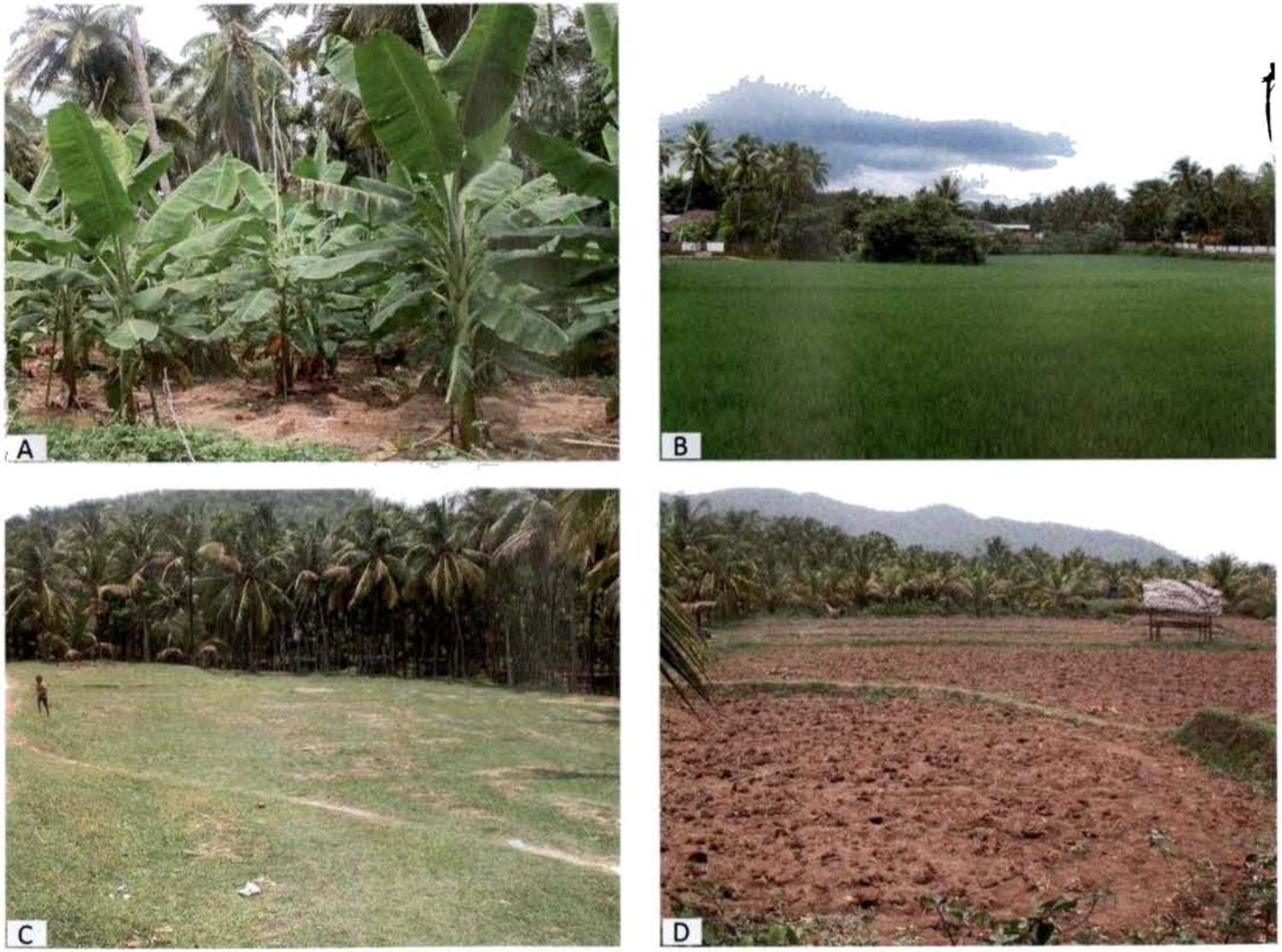
na= not available

Chart A1. Conversion history of different landuse systems studied



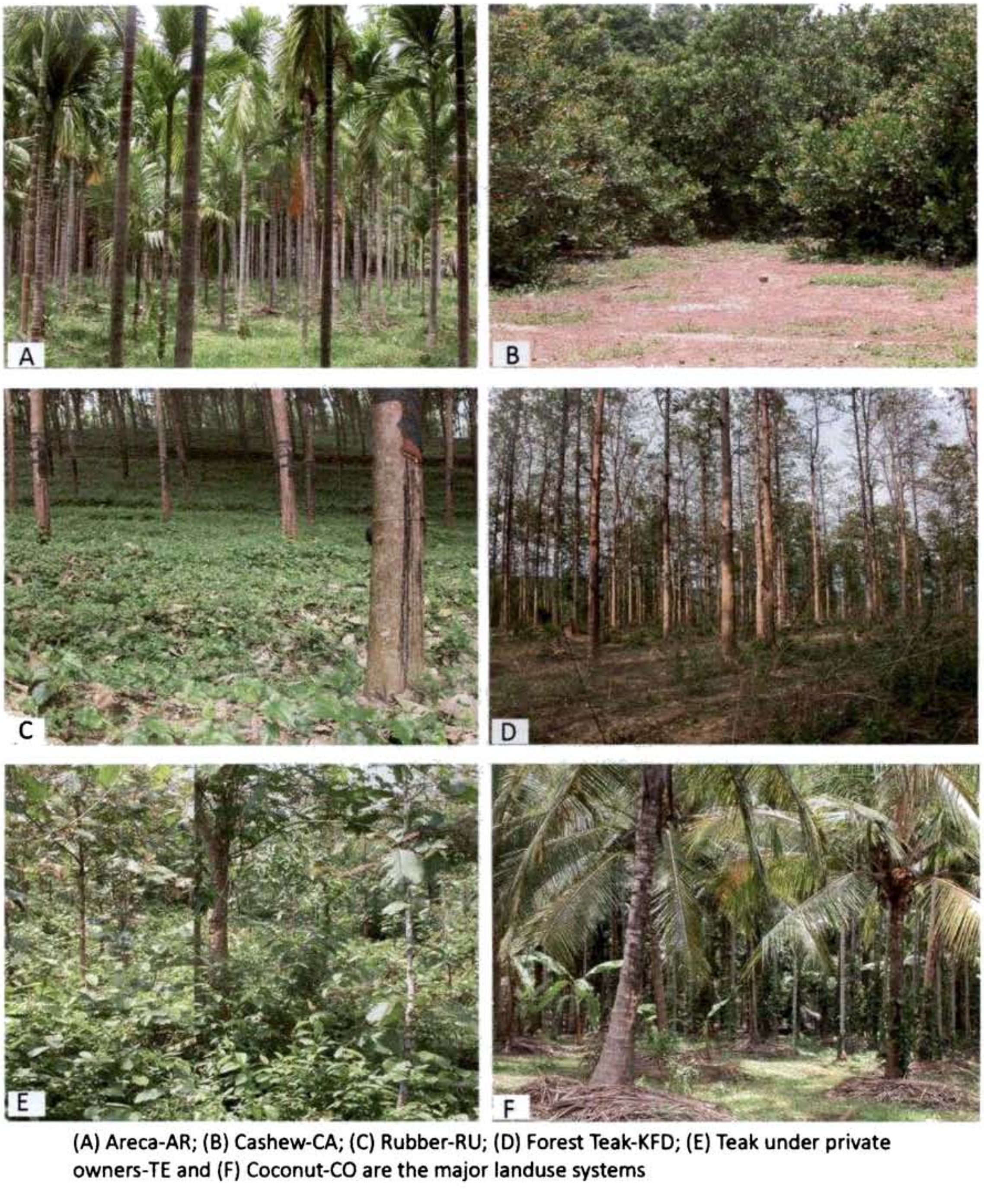
PLATES

PLATE I
AGRICULTURE SYSTEMS



(A) Banana; (B) Paddy and (C,D) Seasonal vegetables are the major landuse systems

PLATE II
MONOCULTURE PLANTATIONS



(A) Areca-AR; (B) Cashew-CA; (C) Rubber-RU; (D) Forest Teak-KFD; (E) Teak under private owners-TE and (F) Coconut-CO are the major landuse systems

PLATE III
AGROFORESTRY SYSTEMS

(A) Homegardens-HG; (B) Polyculture farms-OG; (C) Areca mixed with annuals-AV; (D) Areca mixed with perennials-AM and (E) Coconut mixed with perennials-CM are the major landuse systems

PLATE IV
FOREST ECOSYSTEMS

(A) Degraded forest-DF; (B) Moist deciduous forest-MDF and (C) Semi-evergreen forest-SEF are the major landuse systems

PLATE V

COLLECTION AND EXTRACTION OF SOIL MACROFAUNA

Soil monolith

Handsorting of macrofauna from the soil sample

PLATE VI

SAMPLING OF MAJOR SOIL MACROFAUNAL GROUPS

I- ANTS

II- EARTHWORMS

III- TERMITES

(A) Pitfall trap, (B) Ant nest; (C) Digging soil for earthworms, (D) Mature worms are sorted out for preservation; (E) Searching for termite in soil, (F) Preserving termites in vials with alcohol

PLATE VII

Ants collected from the study area


Tertaponera rufonigra


Tetramorium smithi


Tetramorium rothneyi (Pheidole sp.)


Technomyrmex albipes


Solenopsis geminata


Odontomachus punctulatus


Myrmicaria brunnea


Ectatomma sp.
(phachycondyla rufipes)


Monomorium floricola (Meranoplus sp.)


Monomorium dichroum


Lobopelta ***ocellifera***
(Leptogenys processionalis


Lobopelta birmana
Pachycondyla sp.

PLATE VII (cont'd)


Diacamma ~~assamense~~
rugosum


Crematogaster rothneyi


Cardiocondyla parvinoda


Cardiocondyla wroughtoni


Camponotus sericeus ✓


Camponotus parius ✓


Camponotus mitis ✓


Camponotus compressus ✓


Camponotus binghami ✗


Anochetus punctiventris


Anoplolepis ~~longipes~~
gracelepis


Oecophylla smaragdina

PLATE VIII

Termites and Earthworms collected from the study area

TERMITES

Odontotermes obesus (Soldier)

Odontotermes feae (Soldier)

Trinervitermes sp. (Soldier)

Heterotermes sp. (Soldier)

Dicuspiditermes sp. (Worker)

EARTHWORMS

Megascolex sp.

Drawida sp. A

Glyphidrilus sp.

Drawida sp. B

Dichogaster sp.

Pontoscolex corethrurus