Agroforest Syst
DOI 10.1007/s10457-011-9386-3

Abundance and diversity of soil invertebrates in annual crops, agroforestry and forest ecosystems in the Nilgiri biosphere reserve of Western Ghats, India

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Received: 27 October 2010 / Accepted: 26 March 2011

Abstract Biologically mediated soil processes rely on soil biota to provide vital ecosystem services in natural and managed ecosystems. However, land use changes continue to impact on assemblages of soil biota and the ecosystem services they provide. The objective of the present study was to assess the effect of land use intensification on the distribution and abundance of soil invertebrate communities in the Nilgiri, a human-dominated biosphere reserve of international importance. Soil invertebrates were sampled in 15 land use practices ranging from simple and intensively managed annual crop fields and monoculture tree plantations through less intensively managed agroforestry and pristine forest ecosystems. The lowest taxonomic richness was found in annual crops and coconut monoculture plantations, while the highest was in moist-deciduous and semi-evergreen forests. With 21 ant species, agroforestry systems had the highest diversity of ants followed by forest ecosystems (12 species). Earthworms and millipedes were significantly more abundant in agroforestry systems, plantations and forest ecosystems than in annual crop fields. Ants, termites, beetles, centipedes, crickets and spiders were more abundant in forest ecosystems than in other ecosystems. It is concluded that annual cropping systems have lower diversity and abundance of soil invertebrates than agroforestry and natural forest ecosystems. These results and the literature from other regions highlight the potential role that agroforestry practices can play in biodiversity conservation in an era of ever-increasing land use intensification and habitat loss.

Keywords Anthropogenic disturbance · Biodiversity · Homegarden · Macrofauna · Taxonomic sufficiency

Introduction

Soil organisms contribute to a wide range of ecosystem services that are essential to the functioning of natural and managed ecosystems (Barrios 2007). For example, soil processes rely on soil biota for decomposition of organic matter, nutrient cycling, soil structure stabilization, pest control and soil detoxification (Barrios 2007; Brussaard et al. 2007; Giller et al. 1997; Lavelle 1996). Despite these functions and their significant contribution to global biodiversity, our knowledge of soil biota is still poor compared with

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Published online: 11 April 2011

that of most aboveground organisms (Decaëns 2010). Although a number of workers (Blanchart and Julka 1997; Sinha et al. 2003; Rossi and Blanchart 2005; Tripathi et al. 2005; Yadav 2001) have studied various soil animal taxa in India, information is scanty on the impact of land use on soil invertebrate communities in the Western Ghats in India.

The Western Ghats is one of the 25 global hotspots of biodiversity with the highest human population density and hence vulnerable to anthropogenic disturbances (Kodandapani et al. 2008). The Nilgiri Biosphere Reserve in the Western Ghats was set up in 1986 and it is being considered for selection as a World Heritage Site (UNESCO 2007). Land use changes over the last century have created a mosaic of forest fragments embedded in human dominated landscapes in the Western Ghats (Anitha et al. 2010; Davidar et al. 2007; Garcia et al. 2007; Kumar and Takeuchi 2009). As population pressure increased, large areas of virgin forests were cleared for cultivation of annual crops (mainly paddy and vegetables) and perennial horticultural crops. When rice production became uneconomical, most of the farmers gradually changed to cultivation of cash crops and monoculture plantations. Over the past 25 years, rice cultivation in Kerala has dropped by 60%, while planting of other crops like areca palm (*Areca catechu* L.), coconut palm (*Cocos nucifera* L.), cashew (*Anacardium occidentale* L.), coffee (*Coffea robusta* L. and *Coffea Arabica* L.), rubber (*Hevea brasiliensis* (Willd. ex Adr de Juss.) Muell. et Arg.) and teak (*Tectona grandis* L.) has significantly increased (Kumar 2005). Agroforestry systems where trees are grown with crops, and/or sometimes animals, and the all pervasive homegardens are prominent features of the farming system in the Western Ghats (Chandrashekara 2009; Garcia et al. 2007; Kumar 2005; Kumar and Takeuchi 2009). The homegardens of Kerala are classic examples of agroforestry where many traditional ecological features are being maintained (Chandrashekara 2009).

In human-dominated ecosystems, land use intensification affects the soil community composition, and anthropogenic disturbances may cause long-lasting impacts on ecosystem services (Dupouey et al. 2002). Due to their limited mobility, soil invertebrates are more likely to be affected by habitat fragmentation. This is because the soil is a radically different environment for life than the one above the ground as it hampers the movement and dispersal of animals. Hence habitat fragmentation is more likely to increase the probability of local extinction of soil dwelling species since the "rescue effect" of dispersal is lower. Therefore, understanding and managing soil communities is of immediate concern in agriculture, forestry and biodiversity conservation (Lavelle 1996).

This is especially true in the Nilgiri Biosphere Reserve where the in situ conservation of rare and threatened species as well as the livelihoods of the community is of paramount importance (Davidar et al. 2007). However, there is a dearth of information on the impact of land use changes on assemblages and communities of soil invertebrates. Monitoring key functional groups coupled with observations of physical aspects of land condition may provide an indication of the status of biodiversity and landscape function. Therefore, the objective of the present study was to assess the effect of land use intensification on the distribution and abundance of soil invertebrate communities in the Nilgiri Biosphere Reserve. Our hypothesis was that while land use intensification can have negative impacts on soil invertebrate communities, such impacts can be reduced through agroforestry practices.

Materials and methods

Description of study area

The study area is located in Vazhikkadavuin Malappuram District in Kerala. Detailed studies were conducted in the Karakkode micro-watershed (11°15′N and 11°27′N; 76°17′E and 76°24′E; 60 m to 450 m above sea level) of Chaliyar River in the Kerala part of Nilgiri Biosphere Reserve in the Western Ghats in India (Fig. 1). The climate is typically monsoonic with annual rainfall varying from 1621 mm to 3271 mm. The mean annual maximum and minimum temperatures are 35°C and 26°C, respectively. 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. Soils of the study area are variable. Therefore, we present soil data according to land use described below. Forests are mainly confined to higher slopes and consist of both natural forests and plantations. Rural people, with different social and economic conditions, are primarily dependent on agriculture for their livelihood. The site characteristics of the study area have been described in detail in Chandrashekara et al. (2006).

The study area was divided into 72 grid points consisting of 200 m by 200 m grids, and the intersection points were marked using a Geographical Positioning System (GPS). In total, 15 different land use practices were recognized (Table 1) following Chandrashekara et al. (2006). These were grouped into four main ecosystems: (1) annual crop fields consisting of mainly paddy (PA), (2) agroforestry systems, (3) plantations and (4) forests, based on the biophysical conditions and management practices. Agroforestry systems consisted of multi-strata homegardens (HG), polyculture gardens (OG), areca palm with annuals (AV), areca palm with perennials (AM) and coconut palm with perennials (CM) such as bananas.

Plantations consisted of monoculture stands of areca palm (AR), coconut palm (CO), rubber plantations (RU), cashew plantations (CA), teak plantations managed by the Forest Department (TFD) and teak plantations managed by private land owners (TE). The forest ecosystem consisted of degraded forests (DF), moist deciduous forests (MDF) and semi-evergreen forests (SEF). Among the most complex forest ecosystems was semi-evergreen forest with up to 67 tree species and a mean density of 1300 trees ha^{-1} (Chandrashekara et al. 2006). This was followed by moist deciduous forest (with 33 tree species and mean density of 492 trees ha^{-1}), degraded forest (with 4 tree species and mean density of 327 trees ha^{-1}) and teak plantation managed by the forestry department (with 11 tree species and mean density of 242 trees ha^{-1}). The plantations and agroforestry practices were more difficult to rank by habitat complexity due to the wide variation in crop combinations and management (Chandrashekara et al. 2006). However, we have attempted to define a land use intensification and habitat complexity gradient as in Table 1 based on the vegetation characteristics (diversity, shrub and tree density, basal area and leaf area index) and farmer management. Thus the arrangement of land uses in tables and figures starts with the most complex and

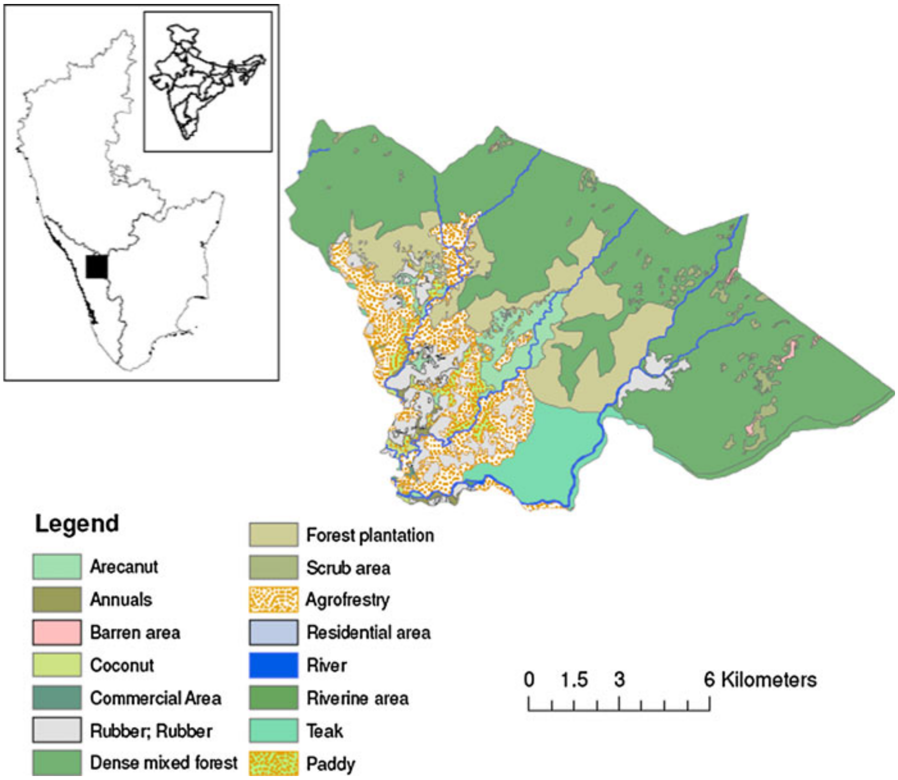

Fig. 1 Major land use systems in the study area

Table 1 Description of the land uses (LUS), diversity (H index), shrub density (individuals ha^{-1}), tree density (individuals ha^{-1}), basal area (m^2 ha^{-1}), and leaf area index (LAI) in the different LUS sampled for soil fauna in the Kerala part of Nilgiri Biosphere Reserve

Ecosystem	LUS code	Description	Diversity	Shrub density	Tree density	Basal area	LAI
Natural forests	SEF	Semi-evergreen forest: A mixture of evergreen and deciduous trees	2.89	2699	1300	45	4.6
	MDF	Moist deciduous forest	2.05	5812	492	23	3.5
	DF	Degraded forest: Deciduous trees sparsely distributed with poor regeneration	0.43	1733	327	3	1.2
Plantations	TFD	Teak plantation managed by the Forest Department	0.53	1211	242	14	1.5
	TE	Teak monoculture managed by private land owners: no organic or inorganic inputs are applied	0.46	4717	1378	10.5	3.8
	AR	Areca palm monoculture: no tillage, inorganic fertilizer and pesticide use in low quantity.	0.46	4223	956	12.1	1.3
	CO	Coconut palm monoculture:	0.71	2919	200	18.8	2.1
	RU	Rubber monoculture: weeding done regularly; inorganic fertilizer application is common	0.16	684	433	10.5	4.4
	CA	Cashew monoculture; No organic or inorganic inputs are applied	1.00	976	189	7.2	1.2
Agroforestry	HG	Homegardens: land cultivated around the farmer's dwelling place with annual, biennial and tree crops integrated with animal husbandry	1.95	469	885	12.1	3.2
	OG	Organic polyculture farms: land cultivated away from the farmer's dwelling place with annual, biennial and tree crops; no tillage; regular weed management; pesticide application when needed	1.03	609	954	13.7	2.5
	CM	Coconut palm integrated with perennial crops; organic input from perennial trees, no inorganic fertilizer application.	1.07	698	316	12.7	2.0
	AM	Areca palm integrated with perennial crops: irrigated in summer	0.94	3619	928	19.6	3.3
	AV	Areca palm integrated with annual crops such as paddy and vegetables; regular tillage, weeding and use of inorganic fertilizer;	0.86	610	1058	14.4	1.6
Annual crops	PA	Annuals like paddy and vegetables; continuous cropping, tillage and use of inorganic fertilizer and pesticides	NA	NA	0	0	NA

NA not available; Data on tree diversity, density, basal area and leaf area index (LAI) in the different LUS were summarized from Chandrashekara et al. (2006)

unmanaged systems (i.e. semi-evergreen forest) and ends with the least complex and most intensively managed land use (i.e. annual crop field).

In order to determine the physical and chemical properties of the top soil, core samples were taken from each land use type. Samples were air dried and analyzed for pH, organic carbon, total nitrogen, extractable phosphorus, exchangeable potassium, calcium, and magnesium using standard methods. Accordingly, soil pH was higher in AM, OG, HG, TFD and TE than in annul crop fields. Soil organic carbon was higher in SEF and MDF than all other land uses; the lowest being in CM. The other characteristics of soils in each land use are summarized in Table 2.

Information on landholding sizes, pesticide and fertilizer use in the various land use systems was collected to gain insight into land owners' management strategy which may influence the spatial distribution of soil fauna. For this purpose, data were collected by interviewing land owners about the quantity, type and frequency of fertilizer and pesticide application per year. The results show that 78% of the farmers hold less than 1 ha, 19% hold 1–2 ha and the remaining 3% hold greater than 2 ha. Most of the land owners used inorganic or organic fertilizer as well as pesticides in plantations, agroforestry systems and annual crop fields. Land owners applied green manure in all of the agroforestry practices. On the other hand, most of the monoculture plantations except coconut did not

Table 2 Soil pH, organic carbon (C in %), total nitrogen (N in %), extractable phosphorus (P in ppm), exchangeable potassium (K in cmol kg^{-1}), calcium (Ca in cmol kg^{-1}), magnesium (Mg in cmol kg^{-1}), and soil bulk density (BD) of the land uses (LUS)

Ecosystem	LUS	pH	C	N	P	K	Ca	Mg	BD
Natural forests	SEF	5.9	2.3	0.16	3.0	0.14	4.0	2.1	1.6
	MDF	5.6	2.2	0.10	4.3	0.32	9.8	3.4	2.0
	DF	5.7	1.9	0.09	2.5	0.04	5.9	2.1	2.4
Monoculture	TFD	6.1	1.9	0.09	2.9	0.03	7.7	2.5	2.2
Plantations	TE	6.1	2.1	0.09	14.0	0.18	5.1	1.0	2.1
	AR	5.7	1.0	0.08	6.1	0.14	2.4	0.5	1.8
	CO	5.9	1.7	0.10	5.9	0.21	4.3	0.8	2.1
	RU	5.6	1.4	0.21	6.2	0.15	2.8	0.6	2.2
	CA	5.7	1.9	0.11	4.7	0.82	2.4	0.7	2.1
Agroforestry	HG	6.1	0.7	0.25	8.9	0.20	4.4	1.1	2.1
	OG	6.2	0.9	0.06	12.4	0.16	4.5	1.1	1.9
	CM	5.4	0.3	0.02	2.8	0.01	1.0	2.2	2.0
	AM	6.2	1.0	0.04	7.2	0.11	2.8	1.0	1.8
	AV	5.9	1.0	0.08	11.2	0.21	3.0	0.7	2.2
Annual crops	PA	5.5	0.8	0.05	4.0	0.48	2.0	2.2	2.2

received green manure. Compost and green manure were applied at higher rates in agroforestry practices compared to annual crops. Land owners applied both inorganic fertilizers and compost in monoculture plantations of areca palm, coconut and rubber, but not to cashew and teak plantations. All land owners applied pesticides (mainly herbicides) in rubber plantations. The majority (67–75%) had applied pesticides in annual crops and areca palm mixed with annual crops and coconut mixed with perennial crops. Compared to the agroforestry and forest ecosystems, in the annual cropping systems the land was utilized year round with more intensive management involving bush burning during land clearing, application of fertilizer, lime, herbicides, insecticide and irrigation. The land has also been cropped for many years with the same crop and intensive usage of fertilizer and pesticide in some cases.

Soil faunal sampling

Sampling was done in the 15 different land use systems. In each land use system, four plots were chosen and then four soil monoliths were taken randomly from each plot, making a total of 16 samples for each land use systems. For the sampling of soil fauna, protocols developed by the Tropical Soil Biology and Fertility (TSBF) institute (Anderson and Ingram 1993) were followed. This method was used in preference to taxon-specific methods because it allows one to broadly assess the effect of land use on a community of co-occurring organisms and species assemblages. Soil monoliths (25 cm × 25 cm × 30 cm) were dug out and soil macrofauna were hand-sorted at the level of family and above and specimens were preserved in alcohol for identification.

Due to taxonomic difficulties, identification could be made at the level of recognizable taxonomic units, i.e. the family and order level, in this study. Although this may be viewed as a weakness relative to species-based analyses, it has several advantages (Harcourt et al. 2005). Sorting of samples to recognizable taxonomic units is generally considered to be a sufficiently reliable and conservative approach in ecological and biodiversity studies (Tanabe et al. 2007; Terlizzi et al. 2008). The use of higher taxa as a surrogate for species mainly stems from the notion of taxonomic sufficiency, i.e. the identification of taxa at levels higher than species without significant loss of information in detecting changes in assemblages exposed to environmental stress (Chainho et al. 2007; Jones 2008; Terlizzi et al. 2008). Broad- based approaches using multiple species and assemblages also offer opportunities for predicting the responses of ecosystems to the challenges of environmental degradation. The use of supraspecific taxa in monitoring biodiversity patterns has gained acceptance as they accommodate the divergent requirements of members of natural communities (Pearman and Weber 2007; Tanabe et al. 2007). In some case, such methods were shown to be as efficient as the species-based approaches (Chainho et al. 2007; Moreno et al. 2008; Tanabe et al. 2007; Terlizzi et al. 2008). Recent studies (Tanabe et al. 2007) have shown that higher taxa of soil invertebrates are effective for assessing the diversity of rural habitats across the East Asian region. In fact, classes and orders of soil invertebrates provided better discrimination among types of secondary forests better than species assemblages of Carabid beetles (Tanabe et al. 2007).

The soil invertebrates groups thus identified were earthworms (Oligochaeta), termites (Isoptera), ants (Hymenoptera), beetles (Coleoptera), earwigs (Dermaptera), grasshoppers, crickets, mole crickets (Orthoptera), bugs, coccids, cicadas (Hemiptera), woodlice (Isopoda), centipedes (Chilopoda), millipedes (Diplopods) and spiders (Arachnida). Species-level identification was made for earthworms, ants and termites.

Statistical analysis

The data collected were expressed as (1) the number of supra-specific taxa per monolith, (2) abundance (numbers per monolith) of each order, and (3) abundance of all macrofauna (the total count of individuals of all taxa per monolith). The mean number of taxa (e.g. number of orders) per monolith was used as an index of taxonomic richness. All counts were analysed using generalized linear models (GLMs) because the counts were over-dispersed thus making conventional parametric and nonparametric tests unsuitable. Traditional methods such as ANOVA and nonparametric statistics cannot handle such data (Sileshi 2008). GLMs assuming the negative binomial distribution (NBD), zero-inflated Poisson (ZIP) or zero-inflated negative binomial (ZINB) distribution were used as deemed appropriate for the data because these allow for the non-normality and over-dispersion (Sileshi 2008). The model best suited for each animal count data was selected by comparing Akaike's information criterion (AIC) values (Sileshi 2008).

A principal component analysis (PCA) was conducted to distinguish between land use systems based on the abundance of the macrofauna. Counts were averaged across plots and replicates to give mean abundance for each land use. Each mean was based on a total of 16 monoliths (4 plots × 4 replicates). All means were then transformed into square roots before PCA analysis.

Results

Variation in richness and abundance with ecosystems

Taxonomic richness, indexed by the number of higher taxa per monolith, significantly varied ($\chi^2 = 79.1$, $P < 0.0001$) across ecosystems. The lowest and highest richness was recorded in annual crop fields and forests, respectively (Fig. 2a). Although agroforestry systems and monoculture plantations had slightly higher number of taxa than annual crop fields, the difference between these ecosystems were not significant (Fig. 2a). 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 had the lowest, while agroforestry systems and plantations were comparable but had significantly higher number of individuals than annual crop fields (Fig. 2b).

Earthworms were significantly more abundant in agroforestry systems, monoculture plantations and forest ecosystems than in annual crop fields (Table 3). Ants and termites were more abundant in forest ecosystems than all other ecosystems. Ants were also less abundant in annual cropping system than in the agroforestry systems and semi-evergreen forests (Table 3). Millipedes were more abundant in agroforestry systems than in all other ecosystems. Beetles, centipedes, Orthoptera and spiders were more abundant in forest ecosystems (Table 3). Other soil invertebrates had more zero counts than the abundance models can accommodate and hence meaningful comparisons could not be made.

Variation in richness and abundance with land use systems

Taxonomic richness significantly varied ($\chi^2 = 159.1$, $P < 0.0001$) with land use systems. The lowest taxonomic richness was recorded in coconut monoculture plantations (Fig. 3) where fertilizer and pesticide inputs were frequently applied. On the other hand, the highest richness was found in moist-deciduous and semi-evergreen forests. Compared to the deciduous and semi-evergreen forests, all other land use systems showed significantly lower taxonomic richness (Fig. 3).

Earthworms were significantly more abundant in moist deciduous forest, coconut mixed with perennial crops and monoculture stands of areca palm, coconut and cashew than in all the other treatments (Fig. 4).

The highest and lowest abundance of ants was recorded in semi-evergreen forest and teak plantation, respectively. Teak plantation did not significantly differ from coconut mixed with perennial crops, annual crop fields and coconut monoculture plantation (Fig. 4). Termites were found in significantly larger numbers in semi-evergreen forests, while they occurred in small numbers in all other land use systems (Fig. 4).

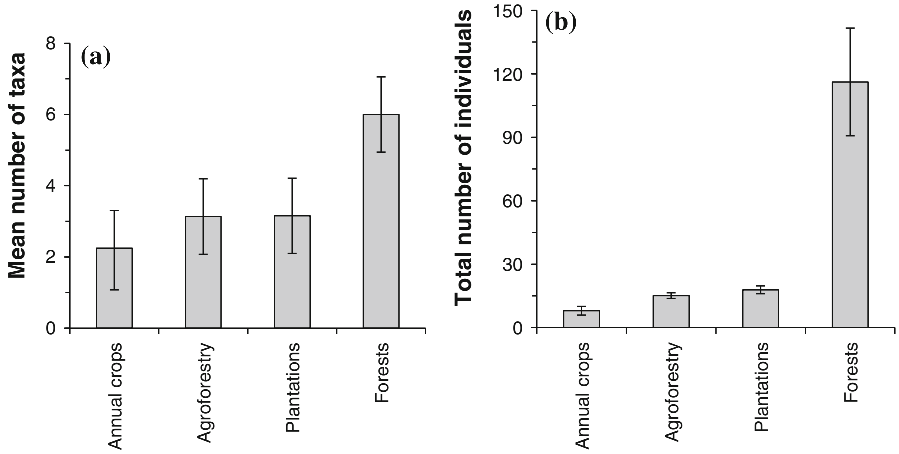

Fig. 2 Taxonomic richness, i.e. mean number of higher taxa (**a**) and total number of individuals (**b**) per monolith recorded in various ecosystems. *Error bars* are model-based standard errors of means

Table 3 Variation in the abundance (number of individuals per m^2) of common soil invertebrates across ecosystems

Ecosystem	Earthworm	Ant	Termite	Beetles	Millipede	Centipedes	Orthoptera	Spiders
Natural forests	97.6	115.2	1542.4	24.0	6.4	16.0	6.4	9.6
Agroforestry	83.2	75.2	40.0	3.2	9.6	4.8	3.2	1.6
Plantations	116.8	52.8	70.4	4.8	4.8	3.2	1.6	3.2
Annual crops	24.0	40.0	16.0	3.2	1.6	8.0	0.0	1.6
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

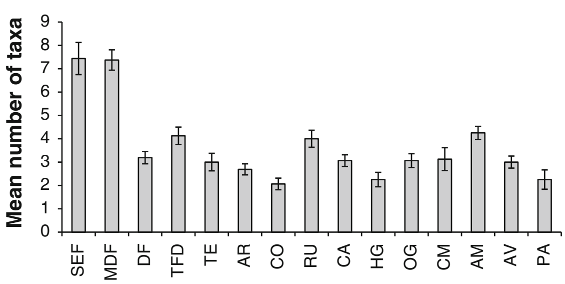

Fig. 3 Variation in taxonomic richness in various land use practices, i.e. *AM* Areca palm with perennials, *AR* monoculture stands of Areca palm, *AV* Areca palm with annuals, *CA* cashew monoculture, *CM* coconut with perennials, *CO* monoculture coconut, *DF* degraded forest, *TFD* teak plantation under Forestry Department, *MDF* moist deciduous forest, *HG* homegardens, *OG* polyculture farms, *PA* annual crop fields, *RU* rubber monoculture, *SEF* semi-evergreen forests, *TE* teak plantation under private ownership. *Error bars* are model-based standard errors of means

Millipedes were more abundant in rubber plantations and areca palm plantations mixed with annuals, while areca palm and coconut monoculture plantations had almost no millipedes (Fig. 4). Centipedes were abundant in semi-evergreen and deciduous forests, while they were entirely absent in monoculture stands of cashew and coconut as well as in polyculture farms (Fig. 4).

Species diversity of selected soil invertebrates

Due to lack of taxonomic expertise only ants, termites and earthworms could be identified at the genus and species level. A total of 27 species of ants in five subfamilies were identified in the course of the study (Table 4). The subfamily Myrmicinae was the most diverse with 12 species in eight genera. The second subfamily Formicinae had eight species in three genera. There were five species in the subfamily Ponerinae, while the subfamilies Dolichoderinae and Ectatomminae had one species each. Agroforestry systems had the highest diversity of ants with 21 species (Shannon diversity index $H' = 2.56$), followed by forest ecosystems with 12 species ($H' = 2.23$) (Table 5). Plantation and annual crops came third and fourth with eight and two species, respectively (Table 5). When individual land uses were considered,

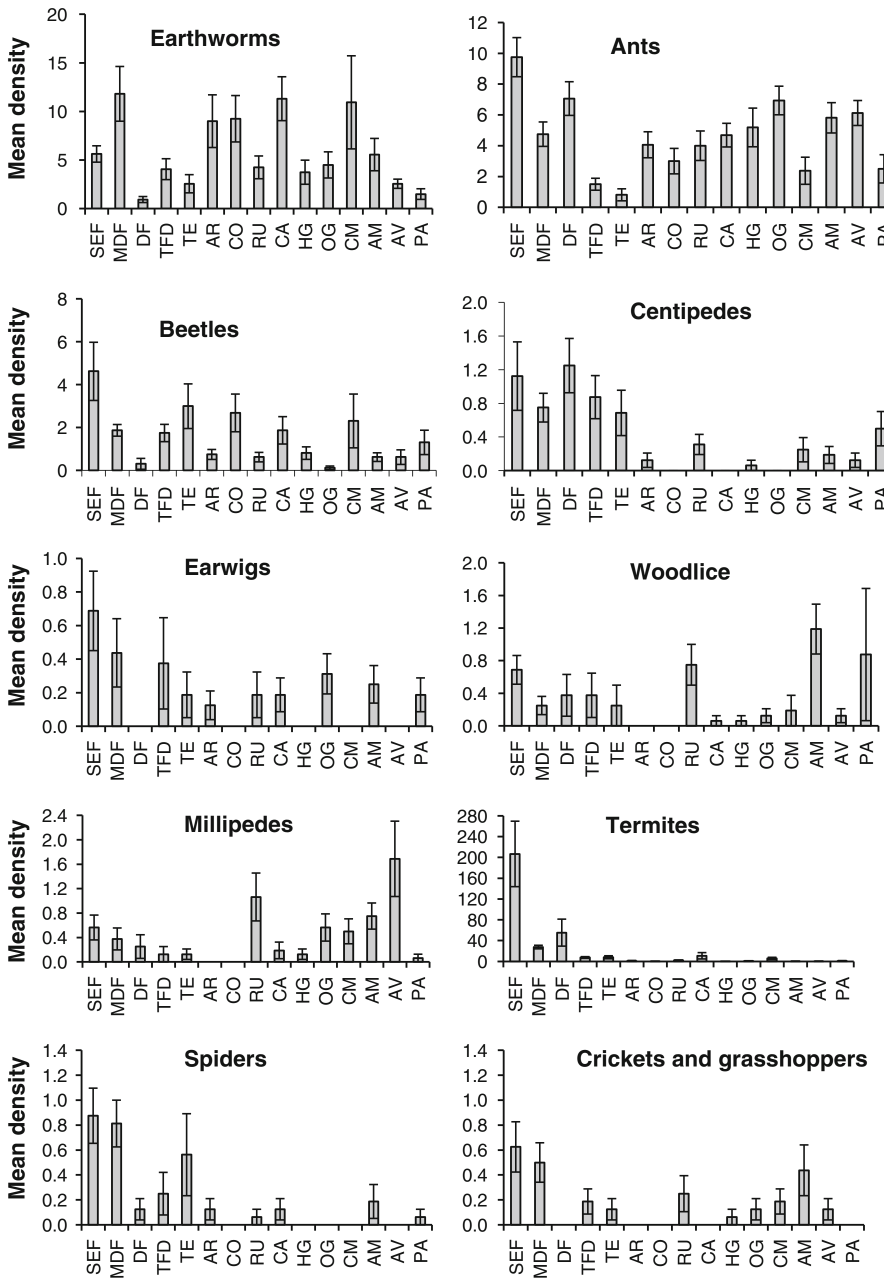

Fig. 4 Variations in the mean density of various taxa with land use practices, i.e. *AM* Areca palm with perennials, *AR* monoculture stands of Areca palm, *AV* Areca palm with annuals, *CA* cashew monoculture, *CM* coconut with perennials, *CO* monoculture coconut, *DF* degraded forest, *TFD* teak plantation under Forestry Department, *MDF* moist deciduous forest, *HG* homegardens, *OG* polyculture farms, *PA* annual crop fields, *RU* rubber monoculture, *SEF* semi-evergreen forests, *TE* teak plantation under private ownership. *Error bars* are model-based standard errors of means

polyculture farms ranked first with 12 species followed by semi-evergreen forest and homegarden each with seven species. With five species, the moist deciduous forest was ranked last.

Altogether, six species of termites were identified in the study area (Table 4). Forest ecosystems showed the highest diversity of termites with five species. Plantations had three species while agroforestry

Table 4 List of ants, termites and earthworms recorded in the various land use systems

Group	Family	Sub-family	Species	Land use systems
Ants	Formicidae	Dolichoderinae	*Technomyrmex albipes* Smith	OG
		Ectatomminae	*Ectatomma* sp.	TEFD, HG
		Formicinae	*Anoplolepis longipes* Jerdon	OG, CA, SEF, MDF, RU, HG
			Camponotus binghamii Forel	AM
			Camponotus mitis Smith	HG, SEF
			Camponotus parius Emery	OG, AV
			Camponotus sericeus Fabr.	OG
			Camponotus compressus Fabr.	HG, OG, AR, CO, TFD, SEF
			Camponotus compressus Fabr. Minor	OG
			Oecophylla smaragdina Fabr.	AM,CM, CA, CO, TE, MDF
		Myrmicinae	*Cardiocondyla parvinoda* Forel	RU
			Cardiocondyla wroughtoai Forel	OG
			Crematogaster rothneyi Forel	RU, MDF
			Meranoplus rothneyi Forel	OG
			Monomorium dichroum Forel	AV
			Monomorium floricola Jerd	HG
			Monomorium sp. A	HG, SEF
			Myrmicaria brunnea Saunders	HG, OG, AV, AM, CM, AR, RU, CA, TE, CO, PA, DF, TFD, SEF, MDF
			Solenopsis geminata Fabr.	OG
			Tetraponera rufonigra (Jerd)	DF
			Tetramorium rothneyi Forel	RU
			Tetramorium smithi Mayr	PA, OG
		Ponerinae	*Anochetus punctiventris* Mayr	OG
			Diacamma assamense Forel	AV, SEF
			Odontomachus punctulatus Forel	AM, SEF, MDF
			Lobopelta birmana Forel	DF
			Lobopelta ocellifera Roger	DF
Termites	Termitidae	Termitinae	*Dicuspiditermes* sp.	TE, TFD
			Labiocapritermes sp.	MDF
		Macrotermitinae	*Odontotermes obesus* (Rambur)	MDF, SEF, DF, TFD, HG, OG, CM, AV, CO, RU, TE, PA, CA, AR, CM
			Odontotermes sp.	MDF, TFD, SEF

Table 4 continued

Group	Family	Sub-family	Species	Land use systems
		Nasutitermitinae	*Trinervitermes* sp.	SEF
	Rhinotermitidae	Heterotermitinae	*Heterotermes* sp.	MDF, SEF
Earthworms	Acanthodrilidae		*Dichogaster affinis* Michaelsen	HG
	Almidae		*Glyphidrilus* sp.	CO
	Moniligastridae		*Drawida* sp. A	SEF, MDF, HG, OG, AR
			Drawida sp. B	SEF, MDF
	Megascolecidae		*Lampito mauritii* Kinberg	PA, AR, CO
			Megascolex sp.	MDF, SEF
	Glossoscolecidae		*Pontoscolex corethrurus*Muller	HG, OG, PA, RU, TE, TFD, CO, CM, AR, AM, CA, AV, DF, SEF

The land use systems are *PA* annual crop fields, *HG* homegardens, *OG* polyculture farms, *AV* Areca palm with annuals, *AM* Areca palm with perennials, *CM* coconut palm with perennials, *AR* Areca palm monoculture, *CO* Coconut palm monoculture, *RU* rubber monoculture, *CA* cashew monoculture, *TFD* teak plantation under Forest Department, *TE* teak plantation under private ownership, *DF* degraded forest, *MDF* moist deciduous forest, *SEF* semi-evergreen forests

systems and annual crops had only one species each. In the case of earthworms, seven species belonging to five families were identified (Table 4). The highest diversity of earthworms was recorded in semi-evergreen forests with four species, followed by moist deciduous forest with three species (Table 4). Due to the low number of species, diversity indices were not calculated for termites and earthworms.

Classification and ordination of land uses

The cluster analysis clearly separated forest ecosystems from all other systems (Fig. 5). Rubber plantations and areca palm mixed with perennials, where fertilizer and pesticide inputs were applied were classified in the same cluster. Similarly, monoculture plantations of areca palm, cashew and coconut were classified in the same cluster (Fig. 5). In the principal component analysis, the first two axes accounted for 60% of the overall variance. The bi-plots based on these axes separated relatively similar land use practices into separate panels (Fig. 6). Semi-evergreen forest, moist deciduous forest, teak plantation managed by the Forest Department and teak plantation managed by private land owners that had high overall abundance of soil invertebrates are in the upper right panel of the bi-plot. The agroforestry practices (HG, OG and AV) are in the lower left panel. Annual cropping, which is the least complex and most intensively managed system, is in the centre of the plot (Fig. 6).

Principal components 1 (Prin1) was associated with the highest positive loadings for Dermaptera (0.37), Isopoda (0.34), Orthoptera (0.38) and termites (0.40). Principal component 2 (Prin2) was associated with the highest positive loadings for beetles (0.51), while principal component 3 was associated with the highest loading for earthworms (0.62). Principal component 4 was associated with the high positive loadings for ants (0.59).

Discussion

This study covered a wide spectrum of land uses, ranging from intensively managed annual crops and monoculture plantations to less managed, highly diversified agroforestry and forest ecosystems. Taxonomic richness and abundance of soil invertebrates

Table 5 Diversity indices for ant species in the various ecosystems

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

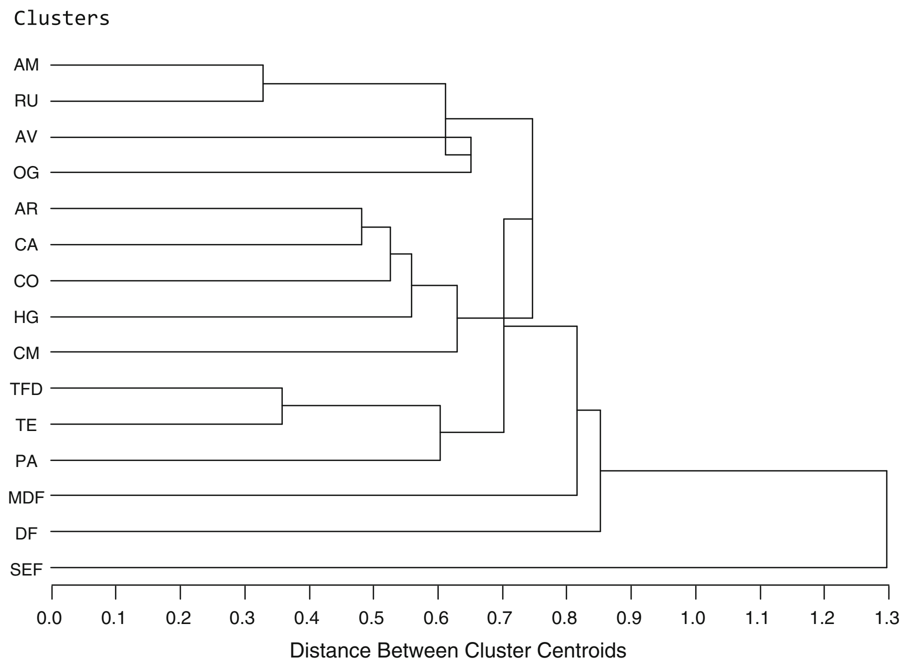

Fig. 5 Single-linkage cluster analysis of macrofauna abundance to identify homogenous ecosystems from land use practices, i.e. *AM* Areca palm with perennials, *AR* monoculture stands of Areca palm, *AV* Areca palm with annuals, *CA* cashew monoculture, *CM* coconut with perennials, *CO* monoculture coconut, *DF* degraded forest, *TFD* teak plantation under Forestry Department, *MDF* moist deciduous forest, *HG* homegardens, *OG* polyculture farms, *PA* annual crop fields, *RU* rubber monoculture, *SEF* semi-evergreen forests, *TE* teak plantation under private ownership. Cluster analysis was conducted based on the normalised minimum distance. The pseudo *F*, pseudo T^2 and the cubic clustering criterion (CCC) were used to determine the optimum number of clusters

were higher in the tree-based systems compared to the annual crops. As expected the highest richness was found in moist-deciduous and semi-evergreen forests, where anthropogenic disturbance was minimal. The diversity of ants, termites and earthworms in particular and soil invertebrates in general increased with habitat complexity; the lowest being in annual crops and the highest in natural forest ecosystems. Therefore, we conclude that diversity and abundance of soil invertebrates increases from annual crops to agroforestry systems and natural forest ecosystems. These findings are in agreement with findings from other parts of India (Blanchart and Julka 1997; Rossi and Blanchart 2005; Tripathi et al. 2005) and elsewhere (Moço et al. 2009). In a dry region of northwestern India, inclusion of particular tree species helped development of a more diverse soil invertebrate community in silvo-pastoral systems (Tripathi et al. 2005).

The lower diversity and abundance in the intensively managed annual cropping systems could be due to lack of habitat heterogeneity and food resources. Land use intensification may cause 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. This may have detrimental effect on the flow of organic matter

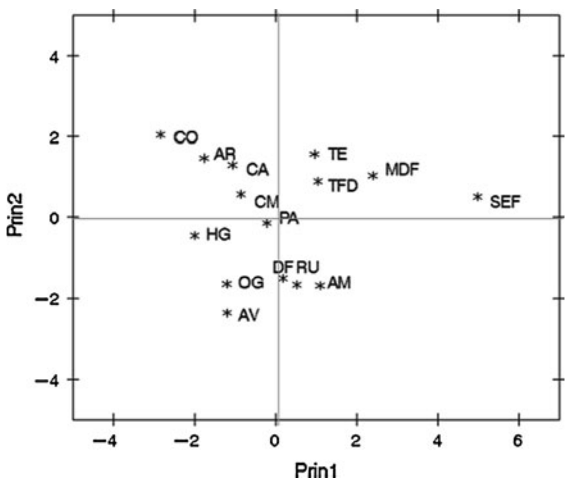

Fig. 6 Bi-plots of the first two principal components (Prin1 and Prin2). Land use practices are *AM* Areca palm with perennials, *AR* monoculture stands of Areca palm, *AV* Areca palm with annuals, *CA* cashew monoculture, *CM* coconut with perennials, *CO* monoculture coconut, *DF* degraded forest, *TFD* teak plantation under Forestry Department, *MDF* moist deciduous forest, *HG* homegardens, *OG* polyculture farms, *PA* annual crop fields, *RU* rubber monoculture, *SEF* semi-evergreen forests, *TE* teak plantation under private ownership. Cluster analysis was conducted based on the normalised minimum distance

and nutrients (Table 2), in turn, adversely affecting soil fertility and crop productivity.

The structural complexity and the niches provided by the trees may enhance the belowground communities. Obviously, the natural forests have greater abundance and diversity of soil fauna because they have a well-developed litter layer besides experiencing less human interference. The development of a litter layer in Agroforestry systems may result in higher abundance and diversity of soil fauna (Moço et al. 2009). Agroforestry systems are also heterogeneous, and this probably provides numerous niches for the soil fauna, supports more food availability and shelter, which in turn may increase taxonomic richness. Similarly, Hoehn et al. (2010) found higher regional bee richness in agroforestry systems in Central Sulawesi (Indonesia). Trees in agroforestry systems bring about a whole complex of environmental changes, affecting incident light, air temperature, humidity, soil temperature, soil moisture content, wind movement and pest and disease complexes. In agroforestry systems and plantations, soil disturbance is low and the use of inorganic fertilizer and pesticides is also minimal. While in annual cropping systems burning of litter and crop residues often eliminate epigeic species, the high input of green manure and litter biomass from the trees could also increase abundance and diversity under agroforestry. For example, Sinha et al. (2003) linked the prevalence of the epi-anecic earthworm *Amynthes corticis* to traditional Agroforestry practices that ensure some soil surface litter in the Himalayas. The various changes under agroforestry can have impacts both on plants and soil invertebrates (Sileshi and Mafongoya 2007) with greater implications for biodiversity. Firstly, the greater abundance and diversity of soil invertebrates means availability of food for predatory animals such as amphibians, reptiles, birds and mammals. Secondly, agroforestry systems owing to their higher functional diversity (than annual crops) can provide habitat and facilitate movement of other animals (Uezu et al. 2008). For example, in fragmented landscapes, agroforestry systems have been shown to act as stepping stones facilitating movement of birds between forest fragments (Uezu et al. 2008). Our results and the literature from other regions (Hoehn et al. 2010; Moço et al. 2009; Sileshi and Mafongoya 2007; Thiollay 2005; Uezu et al. 2008) highlight the potential role that agroforestry practices can play in biodiversity conservation in an era of ever-increasing land use intensification and habitat loss. Therefore, integration of tree and crop production system needs to receive research and policy focus in order to contribute to mitigation of land degradation, conservation of biodiversity and maintenance of ecosystem services in the Nilgiri Biosphere Reserve.

Acknowledgments The author would like to acknowledge UNEP/GEF/TSBF-CIAT programme on Conservation and Sustainable Management of Belowground Biodiversity (CSM-BGBD) for providing financial assistance and Prof. K.G. Saxena, Dean, School of Environmental Sciences, Jawaharlal Nehru University, New Delhi (National Coordinator, CSM-BGBD project) and Dr. U.M. Chandrashekara, Scientist in Charge of KFRI in Nilambur, Kerala (Principal Investigator, CSM-BGBD project, KFRI) for their support during the project.

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