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Earthworm populations in a traditional village landscape in Central Himalaya, India

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ABSTRACT

Scientific knowledge of belowground biodiversity in the Himalaya, a biodiversity hotspot, is scarce. The aim of this study was to investigate density and biomass of earthworm populations and soil properties (texture, bulk density, organic C, total N and pH) in the full range of land use types viz., moderately degraded natural forests (MDNF), highly degraded natural forests (HDNF), rehabilitated forest land (RFL), traditional pure crop system (TPCS), traditional agroforestry system (TAS), abandoned agricultural land (AAL) and rehabilitated agricultural land (RAL) in a village landscape in Central Himalayan region of India. Of the 8 species present in the landscape, *Amynthas alexandri* and *Metaphire anomala* were the most widely distributed taxa, with the former absent only in RAL and the latter only in HDNF, while *Bimastos parvus* and *Perionyx excavatus* were confined to MDNF. TPCS and TAFS harboured the same species. AAL had only one (endogeics) and RAL all the three functional groups (endogeics, epigeics and anecics). All species except *B. parvus* showed a strong effect of season on population size, with the highest abundance and biomass values observed during rainy season. Only *D. nepalensis* and *M. birmanica* were a little bit abundant during dry season in TAFS. In the peak month of September, total density showed a trend of TAFS > TPCS > MDNF > RAL > AAL > RFL > HDNF (147, 132, 63, 27, 14, 8 and 5 individuals m^{-2}, respectively) and biomass of TAFS > TPCS > MDNF > RFL > RAL > AAL > HDNF (266, 199, 51, 24, 21, 16 and 11 g m^{-2}, respectively). The study shows that (i) a change from TPCS to TAFS follows a substantial increase in earthworm density/biomass but not in species richness, (ii) TPCS/TAFS and MDNF host equal number of species but different species composition, with the former having much larger abundance than the latter, (iii) conversion of TPCS to AAL and of MDNF to HDNF cause drastic reduction in species richness and soil organic carbon (SOC), (iv) rehabilitation (change from AAL to RAL and HDNF to RFL) only partly recuperates SOC and earthworm fauna over a period of 20 years, (v) native species fail to survive in highly perturbed environment in HDNF and also in recuperating RFL but coexist with exotics in all other land use types, (vi) SOC explained around 60% of the variation in total density/biomass and (vii) heterogeneous landscapes with agriculture-forest mixed land uses are likely to support greater species richness than homogeneous agriculture/forest ones. Huge variability in land use histories, management practices and biophysical conditions warrant more research on spatio-temporal dynamics of earthworm communities and the linkages between belowground biodiversity, aboveground biodiversity and ecosystem functions.

1. Introduction

Himalaya, a vast mountain system extending across eight Asian countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan), is distinguished globally as a 'biodiversity hotspot' (Myers et al., 2000). Himalayan biodiversity and ecosystem services are crucial not only for sustainable livelihood of 120 million marginal upland people but also for a much larger population inhabiting the adjoining Indo-gangetic plains (Messerli and Ives, 1997). India's recognition as a 'megadiversity' country and as one of the ten largest forested areas in the world derives from the Himalaya which covers only 18% geographical area of the country but accounts for more than 50% of India's forest cover and 40% of vascular plant species endemic to the Indian subcontinent. Agriculture, in terms of net sown area, is a minor land use dispersed as patches in the matrix of forests but is the backbone of local

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livelihoods/economy, with shifting agriculture being the predominant agricultural land use in warm-humid eastern and settled crop-livestock mixed farming in relatively cooler-less humid Central and Western Himalaya (Rao et al., 2003; Singh et al., 2008).

As most biodiversity research and management efforts have been focussed on aboveground biodiversity, scientific knowledge base of belowground biodiversity in the Himalaya, as also in other biodiversity hotspots around the world, is quite weak (Brown et al., 2004; Saxena et al., 2005; Rossi and Blanchart, 2005; Decaens, 2010). This gap in knowledge delimits realization of potential benefits of belowground biodiversity (Wardle et al., 2004; Brussaard et al., 2007). Soil is a habitat of a huge variety of organisms contributing to ecosystem functions in diverse ways (Lee, 1994; Lavelle and Spain, 2001; Lavelle et al., 2006). Earthworms make a significant fraction of biomass of soil biota in many ecosystems (Barros et al., 2002; Brown et al., 2004; Pauli et al., 2011) and play a key role in stable soil aggregate formation, soil drainage, litter decomposition, nutrient cycling, control of pests/pathogens and stimulation of crop growth/defence mechanisms (Lee, 1985; Edwards and Bohlen, 1996; Fragoso et al., 1997; Blouin et al., 2005; Lavelle et al., 2006; Jouquet et al., 2010; Wurst, 2010). Earthworms are an inexpensive tool of maintaining soil fertility, sustaining high crop yields and rehabilitating degraded ecosystems (Lavelle et al., 1998; Whalen et al., 1998; Pulleman et al., 2005; Dash et al., 2009) but, sometimes, may cause deterioration of soil quality (Hallaire et al., 2000), emission of N_2O (Bertora et al., 2007) and loss of plant biodiversity (Eisenhauer et al., 2010).

Changes in earthworm abundance, community structure and activities reflect changes in land use, management practices, soil quality, ecosystem functions and ecosystem/landscape complexity (Lavelle et al., 1987; Gonzalez and Zou, 1999; Schmidt et al., 2003; Dlamini and Haynes, 2004; Decaens et al., 2004; Smith et al., 2008; Ayuke et al., 2011; Pauli et al., 2011). Though some information is available on earthworm abundance and community structure in selected agricultural and forestry land uses in Central Himalaya (Kaushal and Bisht, 1994; Kaushal et al., 1995; Bhadauria et al., 1997, 2000; Sinha et al., 2003), a comprehensive effort covering the full range of land use types within village landscapes is lacking. The present study aimed to analyse density and biomass of earthworm populations in relation to land use and soil properties in a heterogeneous village landscape in Central Himalayan region of India.

2. Materials and methods

2.1. Study area

The study was carried out at Bhiri-Banswara village landscape (latitude 30°27′N and 79°5′E) in Chamoli district in Central Himalayan region of India. The landscape covers an area of 600 ha spread over an elevation of 1100–1200 m above mean sea level and is surrounded by government forests. The climate is typical monsoon, with 80% of annual rainfall (1700 mm) occurring during warm July–September period and monthly minimum and maximum temperatures varying in the range of 7–24 °C and 19–34 °C, respectively. The soil is derived from feldspathic quartz schists, quartz muscovite schists and quartz chlorite schists, and can be classified as Dystric Cambisol according to FAO system.

The village community comprises 2200 people in 400 households. Average per capita cultivated land is 0.12 ha and 85% land holdings are <1 ha. Each family has a pair of bullocks and cows. Livestock feed is partly obtained from farm land (crop residues, weeds and fodder from agroforestry trees) but largely from forests (grazing and grass and tree fodder). Bedding material in livestock-sheds is made of leaf litter collected from forests and litter-livestock excreta mixture is used as manure in cropland. Agrochemicals are not used at all. Land use practices were guided solely by indigenous knowledge until 1890s. Major policy interventions influencing land use/ownership include: (i) grant of inheritable private ownership rights on cultivated land to local people along with designation of all uncultivated lands as government forest lands, with no restrictions on traditional subsistence uses of non-timber forest products, in the 1890s, (ii) creation of community forests carved out of government forests during 1920–30, (iii) logging in some patches of government forest land until 1977 when green tree cutting was banned, (iv) supply of a quota of staple food grains at subsidized price arranged by the government since 1980 and (v) financial support for rehabilitation of degraded lands since 1992. As at present, Bhiri-Banswara village landscape is differentiated into seven land use types (Table 1).

2.1.1. Moderately degraded natural forests (MDNF)

These forests are managed by local people to meet their subsistence needs and have never been logged in the past. *Quercus leucotrichophora* A. Camus is a climax species and is also valued by local people for its high quality fodder, fuelwood, leaf litter and small timber. Further, local people consider oak forests highly efficient in recharge of springs, the traditional sources of drinking water, and in protection of crop/livestock from depredation by wildlife. Traditional institutions regulate resource uses and manage tree component to favour dominance of oak.

2.1.2. Traditional pure crop system (TPCS)

Archival records suggested TPCS to be more than 200-year-old system. Two crops are harvested from a field in one year. Finger-millet, foxtail millet, paddy, pigeon pea, soybean, horsegram and beans are grown during warm/rainy season (June–October) and wheat, mustard and lentil during winter season (November–May). A high level of crop diversification is achieved by rotating pure crops in time and space as well as by intermixing of leguminous and non-leguminous crops in small fields. Farm yard manure is systematically piled up as small heaps in the field in May/October, exposed to sun for 7–20 days and then incorporated by ploughing with a 25–30 cm long heavy iron blade at the end of a wooden beam driven by bullocks in late-May/late-October. Around 25 t of manure is applied annually in each ha of cropland. Crops are harvested at a level of 15–30 cm and remaining residues get also incorporated at the time of ploughing.

2.1.3. Traditional agroforestry system (TAFS)

Some farmers started protecting naturally regenerated multipurpose trees on a portion of their TPCS during 1970s when they felt fodder/fuelwood shortage. TAFS differed from TPCS only in respect of occurrence of agroforestry trees viz., *Boehmeria rugulosa* Wedd., *Grewia optiva* Drummond ex Burret and *Celtis australis* Linn. with 2–5 m inter-tree spacing. Farmers understand that yield-depressing effects of agroforestry trees (shade and competition with crops) outweigh their yield-enhancing effects (nutrient enrichment of soil) but maintain them for availability of fodder/fuelwood near dwellings during lean period (Semwal et al., 2002).

2.1.4. Abandoned agricultural land (AAL)

A cluster of 8 families moved out of the village during 1970s and the community treated their abandoned agricultural land as a common resource. This area bears sparse herbaceous vegetation. Absence of agroforestry trees suggested that the area was under TPCS at the time of abandonment.

Table 1
Selected attributes of land use/cover types differentiated in Bhiri-Banswara village landscape in Central Himalaya, India.

Parameter	Moderately degraded natural forest (MDNF)	Traditional pure crop system (TPCS)	Traditional agroforestry system (TAFS)	Abandoned agricultural land (AAL)	Rehabilitated agricultural land (RAL)	Highly degraded natural forest (HDNF)	Rehabilitated forest land (RFL)
Ownership	Community land	Private land	Private land	Community land	Community land	Government land	Community land
Salient historical features	Never logged in the past but non-timber forest products utilized for subsistence for more than 200 years	More than 200-year-old farm land	Multipurpose trees selectively protected over the last 20–30 years when shortage of forest resources was felt by some households.	A group of families out-migrated during 1970s and their land became open common land.	Abandoned agricultural land until treatment began in 1992	Forest patches logged at least before 50 years followed by unrestricted forest resource uses	Highly degraded natural forest until treatment began in 1992
Present vegetation and appearance	15–25 m high *Quercus leucotrichophora* trees on 25–30° natural slopes; tree density: 350 ha^{-1}, basal area: 41 m^2 ha^{-1}	5–8° outward sloping 4–7 m-wide and 1–2 m-high terraces devoid of trees	5–8° outward sloping 4–7 m-wide and 1–2 m-high terraces with 170 trees ha^{-1} and basal area of 13 m^2 ha^{-1}	Herbaceous vegetation on damaged terraces	Multipurpose trees with average tree height of 15–20 m and basal area of 20 m^2 ha^{-1}, with crops in the understorey	1–2 m tall herbaceous vegetation with isolated stunted trees (<5 m tall) and basal area of <2 m^2 ha^{-1}	Multipurpose trees with average tree height of 10–15 m and basal area of 15 m^2 ha^{-1}
Surface cover	Herbaceous vegetation dominated by dicotyledonous species, continuous 0.5–2 cm thick leaf litter layer and livestock droppings through out the year	Annual food crop cover during November-mid-May and June-mid-October	Annual food crop cover during November-mid-May and June-mid-October	Herbaceous vegetation dominated by grasses, discontinuous < 0.5 cm thick litter layer and livestock droppings through out the year	Perennial cardamom/turmeric crop cover and a discontinuous <0.5 cm thick leaf litter layer	Herbaceous vegetation dominated by grasses, discontinuous <0.5 cm thick litter layer and livestock droppings through out the year	Herbaceous vegetation dominated by dicotyledonous species and continuous 0.5–1.0 cm thick leaf litter layer through out the year
Management practices and disturbances							
Collection of litter	About 60% of annual leaf litter fall and almost all deadwood	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Livestock grazing pressure	Restricted grazing for 30–40 days in a year	Restricted grazing over 10–15 days of fallow period between harvesting of summer crop/sowing of winter crop	Restricted grazing over 10–15 days of fallow period between harvesting of summer crop/sowing of winter crop	Open grazing all through the year	Protected from grazing	Open grazing all through the year	Restricted grazing after trees gained a height of 5 m
Tree lopping and crown cover	Crown cover of 70–80% in December–April reduced to 40–50% during May–June due to lopping	Not applicable	Crown cover of 30–40% during July–August reduced to 10–20% during December–January due to lopping	Not applicable	Lopping such that 40–50% of crown cover is maintained round the year	Unrestricted lopping of tree branches round the year, with crown cover of <10%	Lopping such that 60–70% of crown cover is maintained round the year
Tillage, crops, manure and irrigation	Not applicable	20–30 cm deep ploughing 3-times each in late-May and late-October; rotation of pure crops as well as legume-non-legume mixed crops in small fields; 10 t ha^{-1} farm yard manure applied in summer season and 15 t ha^{-1} in winter season; rainfed farming	20–30 cm deep ploughing 3-times each in late-May and late-October; rotation of pure crops as well as legume-non-legume mixed crops in small fields; 10 t ha^{-1} farm yard manure applied in summer season and 15 t ha^{-1} in winter season; rainfed farming	Not applicable	As in traditional pure crop/agroforestgry system until 2004 when cardamom and turmeric replaced annual food crops in the understorey; manure input of 10 t ha^{-1}h for perennial crops; life saving irrigation provided to crops	Not applicable	Not applicable

2.1.5. Rehabilitated agricultural land (RAL)

Following a participatory approach, a segment of AAL was rehabilitated in 1992. Interventions included repair of abandoned terraces, mixed plantation, at 3 m-interval on terrace margin, of multipurpose agroforestry tree species, viz., *Alnus nepalensis* D. Don, *Albizzia lebbeck* (L.) Benth., *B. rugulosa*, *C. australis*, *Prunus cerasoides* D. Don, *Pyrus pashia* Buch-Ham. ex D. Don, *Sapium sebiferum* (Michaux) Roxb., *Dalbergia sissoo* Roxb., *Ficus glomerata* Roxb. and *G. optiva*, traditional cultivation of annual food crops until 2004 and, thereafter, perennial turmeric and cardamom, life saving irrigation and protection from grazing (Maikhuri et al., 1997). Trees were lopped after they reached a height of 4 m maintaining 30–40% crown cover round the year.

2.1.6. Highly degraded natural forests (HDNF)

This area, possibly logged in distant past, is characterized by absence of climax species, highly stunted woody species, sparse vegetation cover and unregulated resource use.

2.1.7. Rehabilitated forest land (RFL)

A portion of HDNF was rehabilitated in 1992 by establishing mixed plantation as in the case of RAL. Nitrogen fixing *A. nepalensis* contributed 20% of total tree density in this site unlike equal density of all species in RAL. The site was protected until all trees reached a height of 5 m. Subsequently regulated grazing was allowed and trees lopped maintaining 60–70% crown cover round the year. Leaf litter collection was not permitted.

MDNF was the most extensive land use covering 46% area of the landscape followed by TPCS (35%), TAFS (10%), HDNF (6%) and AAL/RFL/RAL (1% each). The differences between MDNF and HDNF thus reflect the impacts of forest degradation, between TAFS and TPCS of agroforestry trees in cropland, between HDNF and RFL of rehabilitation of degraded forests and between AAL and RAL of rehabilitation of abandoned agricultural land.

2.2. Sampling

Three replicate plots (50 m × 50 m), with 150–200 m distance between adjacent plots, of each land use type (n = 21 plots) were demarcated. All plots were selected on south-facing slopes over an elevation range of 1100–1150 m to maximize the effect of land use. Starting in January, 2008, monoliths (25 cm × 25 cm × 30 cm) were dug at four sampling points at 10 m – interval, on two 40 m transects with random origins and separated by a distance of 30–40 m running along the slope, in the central area of each plot at 2 month-interval (n = 6 transects and 24 monoliths on each sampling time in each land use type). Following Anderson and Ingram (1993), each monolith was divided into 0–10, 10–20 and 20–30 cm layers, earthworms hand-sorted in each layer, preserved in 4% formol and identified to species level. Biomass was determined by weighing preserved worms after having wiped specimens dry on a filter paper. Soil physico-chemical characteristics were analysed in 0–10 cm layer in samples collected in the month of January only. Soil texture was determined by hydrometer method, soil organic carbon (SOC) by Walkey-Black dichromate oxidation method, total nitrogen by Kjeldahl method and pH in soil:water suspension (1:2.5) using a digital pH meter. Bulk density was measured following Allen (1974). Observations of the four monoliths of a transect were pooled together, treating each transect as a replicate for statistical analysis. The sampling was designed taking into account the need of spatial independence based on our previous studies (Bhadauria et al., 1997, 2000; Sinha et al., 2003). Earthworm species and tree species were identified based on the taxonomic keys given by Julka (1988) and Gaur (1999), respectively.

2.3. Data analysis

One-way analysis of variance was applied to assess the effect of land use type on soil physico-chemical properties and of month (sampling time) on abundance of earthworm species confined to only one land use type. Two-way analysis of variance was applied to assess the effects of land use, month and land use × month interaction on density/biomass of species occurring in two or more land use types and on total earthworm density/biomass. Before analysis, both density and biomass data sets were tested for departure from normality and were transformed into logarithms to equalize variance and to achieve conditions required for ANOVA. Nature and significance of relationships between soil physico-chemical properties and earthworm density/biomass were assessed (Sokal and Rohlf, 1981).

3. Results

3.1. Site characteristics

TAFS had the highest concentration of SOC (18.1 g kg^{-1}) followed by RAL (15 g kg^{-1}), TPCS, MDNF and RFL (12.4–13.2 g kg^{-1}) and AAL and HDNF (8.3–8.6 g kg^{-1}). Thus, SOC concentration declined by 33% following conversion of MDNF to HDNF and TPCS to AAL and increased by 74% and 49% following conversion of AAL to RAL and HDNF to RFL, respectively. Conversion of TPCS to TAFS enhanced SOC concentration by 36%. Total N concentration showed trends broadly similar to those of SOC. Soils in AAL and HDNF had higher (P < 0.05) bulk density and lower clay content and RFL lower (P < 0.05) pH compared to the soils in other sites. These soil properties, however, were not as much influenced by land use as SOC and total N concentrations (Table 2).

3.2. Selected attributes of earthworm species

Of the eight species occurring in Bhiri-Banswara village landscape, 4 belonged to family Megascolecidae, 2 to Octochaetidae and one each to Lumbricidae and Moniligastridae. In terms of biogeographic origin, *Amynthas alexandri*, *Bimastos parvus*, *Metaphire anomala* and *Metaphire birmanica* were exotic and *Drawida nepalensis*, *Perionyx excavatus*, *Lennogaster pusilla* and *Octochaetona beatrix* native peregrines. Based on maximum achievable size, species could be grouped into three classes: (i) small-size worms (maximum length 80 mm and diameter < 3 mm): *B. parvus*, *L. pusilla* and *P. excavatus*, (ii) medium-size worms (length 120–160 mm and diameter 4–7 mm): *M. birmanica*, *M. anomala*, *D. nepalensis* and *O. beatrix* and (iii) large-size worms (length: > 180 mm and diameter > 8 mm): *A. alexandri*. Ecological category of epigeics was represented by three species (*B. parvus*, *L. pusilla* and *P. excavatus*), endogeics by four species (*M. birmanica*, *M. anomala*, *O. beatrix* and *A. alexandri*) endogeics and anecics by only one species (*D. nepalensis*) (Table 3).

3.3. Species occurrence

A. alexandri and *M. anomala* were the most widely distributed taxa, with the former absent only in RAL and the latter only in HDNF. *B. parvus* and *P. excavatus* were confined to MDNF. A change from TPCS to TAFS was not associated with any change in species assemblage. MDNF differed from TPCS/TAFS in terms of kind but not number of species present. *B. parvus*, *P. excavatus* and *L. pusilla* occurred in MDNF but not in TPCS/TAFS, while *O. beatrix*, *D. nepalensis* and *M. birmanica* occurred in TPCS/TAFS but not in MDNF. Species richness reduced from 5 in MDNF to 2 in HDNF. Rehabilitation of HDNF could recover only one (*M. anomala*) of the four species (*M. anomala*, *B. parvus*, *L. pusilla* and *P. excavatus*)

Table 2
Physico-chemical characteristics of soil in different land use types in Bhiri-Banswara village landscape in Central Himalaya, India. Values for any variable with different superscript letters are significantly ($P<0.05$: Tukey's honestly significant difference method) different within columns.

Land use/cover	Clay (%)	Silt (%)	Sand (%)	Bulk density ($g\,cm^{-3}$)	pH	Organic carbon ($g\,kg^{-1}$)	Total nitrogen ($g\,kg^{-1}$)
Moderately degraded natural forest (MDNF)	17.4^{cd}	28.0^{a}	54.6^{a}	1.11^{a}	6.1^{ab}	12.6^{b}	1.2^{b}
Traditional pure crop system (TPCS)	14.2^{abcd}	31.6^{a}	54.2^{a}	1.10^{a}	6.2^{b}	13.2^{b}	1.2^{b}
Traditional agroforestry system (TAFS)	14.7^{abcd}	32.5^{a}	52.8^{a}	1.04^{a}	6.4^{b}	18.1^{d}	1.4^{b}
Abandoned agricultural land (AAL)	15.4^{bcd}	29.2^{a}	55.4^{a}	1.31^{b}	6.4^{b}	8.6^{a}	0.8^{a}
Rehabilitated agricultural land (RAL)	15.2^{bcd}	30.0^{a}	54.8^{a}	1.12^{a}	6.3^{b}	15.0^{c}	1.4^{b}
Highly degraded natural forest (HDNF)	11.4^{ab}	32.5^{a}	56.1^{a}	1.32^{b}	6.2^{b}	8.3^{a}	0.7^{a}
Rehabilitated forest land (RFL)	12.2^{ab}	31.6^{a}	56.2^{a}	1.14^{a}	5.8^{a}	12.4^{b}	1.7^{c}

Table 3
Selected attributes of earthworm species occurring in Bhiri-Banswara village landscape in Garhwal Himalaya, India.

Species and author	Color	Length (mm)[a]	Diameter (mm)[a]	Family	Biogeographic origin	Ecological category
Amynthas alexandri (Beddard, 1901)	Dark brown	180	8	Megascolecidae	Exotic peregrine	Endogeic
Bimastos parvus (Eisen, 1874)	Dark brown	70	2	Lumbricidae	Exotic peregrine	Epigeic
Drawida nepalensis (Michaelsen, 1907)	Light whitish	140	7	Moniligastridae	Native peregrine	Anecic
Lennogaster pusilla (Stephenson, 1920)	Light brown	50	2	Octochaetidae	Native peregrine	Epigeic
Metaphire anomala (Michaelsen, 1907)	Dark brown	140	4	Megascolecidae	Exotic peregrine	Endogeic
Metaphire birmanica (Rosa, 1988)	Blackish brown	160	4	Megascolecidae	Exotic peregrine	Endogeic
Octochaetona beatrix (Beddard, 1902)	Light pink	120	4	Octochaetidae	Native peregrine	Endogeic
Perionyx excavatus (Perrier, 1972)	Dark violet/purple	76	3	Megascolecidae	Native peregrine	Epigeic

[a] Measurements of largest individuals in the collection.

lost due to degradation of MDNF. *M. birmanica* present in HDNF survived in RFL too. Abandonment of TPCS caused loss of *M. birmanica* and *O. beatrix*. Development of agroforestry in AAL followed recovery of *M. birmanica*, exclusion of *A. alexandri* and establishment of *L. pusilla*, a species absent in both TPCS and AAL. Thus, rehabilitation of HDNF or AAL enabled some increase in species richness but not reestablishment of species assemblages of MDNF or TPCS. Native peregrine and exotic species coexisted in all land use types except HDNF and RFL where only exotic species occurred (Fig. 1).

3.4. Earthworm density and biomass

Time of sampling (month) and land use had a highly significant ($P<0.0001$) effect on population size of individual species, except insignificant effect ($P>0.05$) of month on *B. parvus* biomass and of land use on *L. pusilla* density and biomass (Table 4; Fig. 2). Effect of land use × month interaction was also highly significant in species common to two or more land use types. All species showed the highest abundance and biomass values during rainy season. Only *D. nepalensis* and *M. birmanica* were a little bit abundant

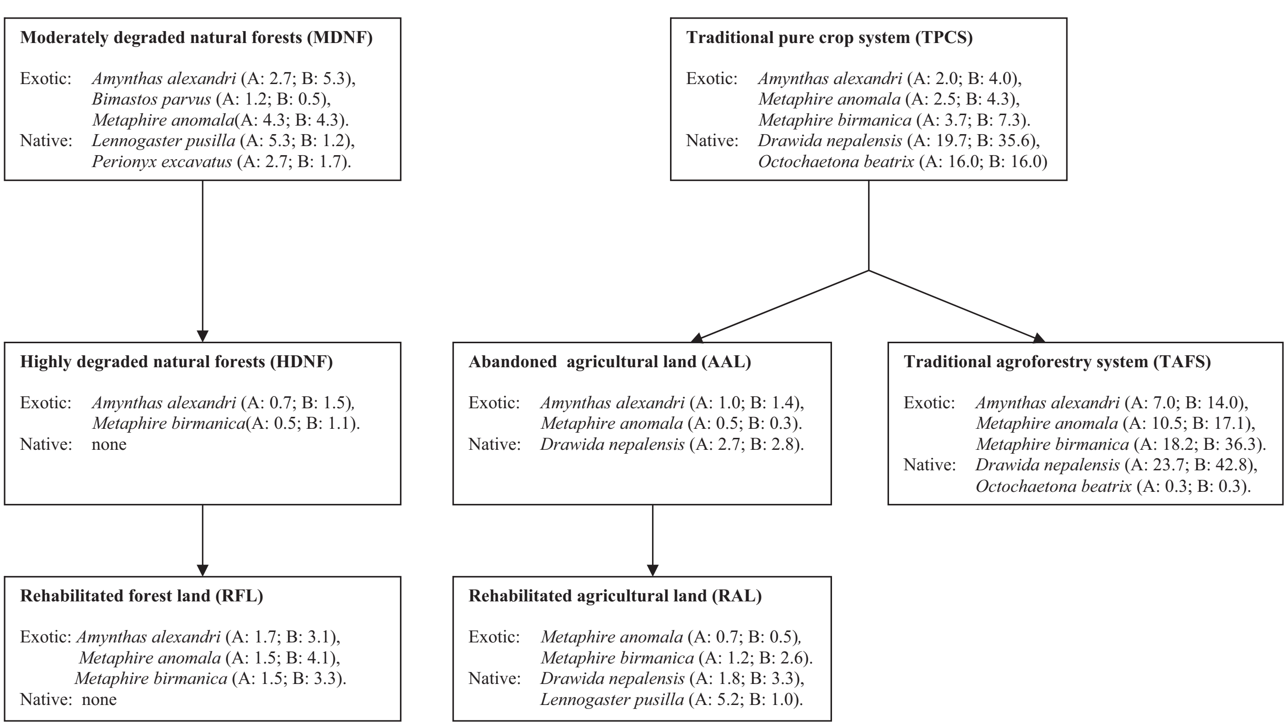

Fig. 1. Distribution pattern of earthworm species in different land use types in Bhiri-Banswara village landscape, Central Himalaya, India. Mean density (no. of individuals m^{-2}) (a) and biomass ($g\,m^{-2}$) (b) values of a species in different land use types are also given.

Table 4
Results of analysis of variance (ANOVA)[a] of species-wise and total earthworm density and biomass.

Source of variation	df	F (density)[b]	F (biomass)[b]
Amynthas alexandri			
Land use/cover	5	47.0	64.0
Month	5	185.3	349.6
Land use/cover × month	25	13.2	17.1
Within	180		
Total	215		
Bimastos parvus			
Month	5	9.5	2.7^{NS}
Within	30		
Total	35		
Drawida nepalensis			
Land-use/cover	3	561.9	470.8
Month	5	226.0	172.8
Land use/cover × month	15	54.8	41.6
Within	120		
Total			
Lennogaster pusilla			
Land use/cover	1	0.2^{NS}	0.0^{NS}
Month	5	248.5	13.4
Land use/cover × month	5	2.3^{NS}	2.3^{NS}
Within	60		
Total	71		
Metaphire anomala			
Land use/cover	5	115.2	128.8
Month	5	180.5	192.7
Land use/cover × month	25	14.9	23.1
Within	180		
Total	215		
Metaphire birmanica			
Land use/cover	4	235.9	262.4
Month	5	156.7	245.0
Land use/cover × month	20	26.7	29.8
Within	150		
Total	179		
Octochaetona beatrix			
Land use/cover	1	878.9	494.4
Month	5	243.1	138.1
Land use/cover × month	5	176.8	99.3
Within	60		
Total	71		
Perionyx excavatus			
Month	5	41.2	23.2
Within	30		
Total	35		
All species (total density/biomass)			
Land-use/cover	6	523.2	924.5
Month	5	813.5	1342.0
Land-use/cover × month	30	41.7	61.5
Within	210		
Total	251		

[a] One-way ANOVA showing the effect of only month in *Bimastos parvus* and *Perionyx excavatus*, the species confined to only one land use/cover type, and two way-ANOVA showing effect of land use/cover, month and land use/cover × month interaction in other species and all species pooled together.
[b] NS, not significant ($P > 0.05$); all other F values are highly significant ($P < 0.0001$).

during dry season in TAFS. Density and biomass values declined sharply between September (end or rainy season) and November (beginning of winter season) in all species in all sites, except for a marginal but significant ($P < 0.05$) increase in *M. anamola* biomass in TPCS and TAFS. Monthly fluctuations in population sizes were more marked in TPCS, TAFS and MDNF compared to the other land use types. Magnitudes of differences between land use types varied with the sampling time. For example, MDNF harboured a significantly ($P < 0.01$) larger population of *A. alexandri* compared to TPCS in September but the two land uses did not differ ($P > 0.05$) in July and November. TPCS had significantly ($P < 0.01$) larger populations of *D. nepalensis* during July–September period and smaller ones during January-May period compared to those in TAFS while the

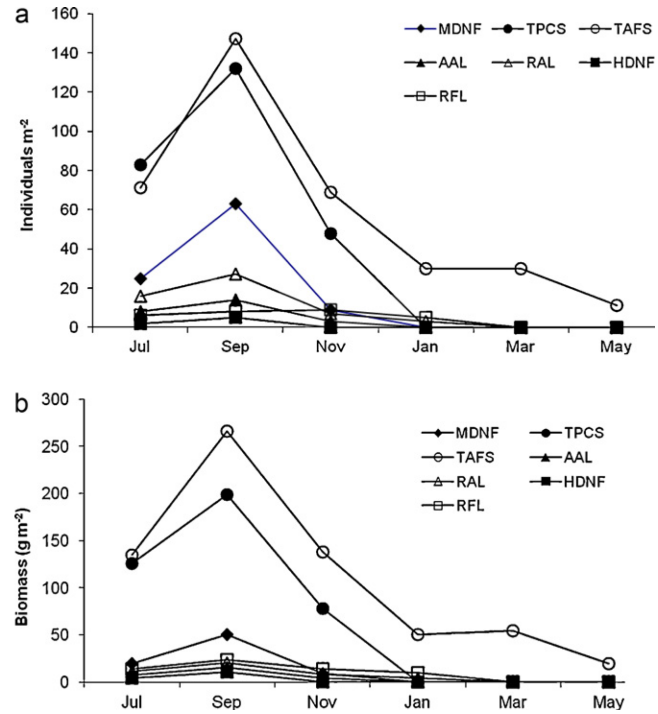

Fig. 2. (a, b) Temporal variation in total earthworm density (a) and biomass (b) in different land use types in Bhiri-Banswara village landscape, Central Himalaya, India.

population sizes in November in the two land uses did not differ significantly ($P > 0.05$).

Total earthworm density/biomass was significantly influenced by land use type, month of sampling and land use × month interaction. Like most individual species, total density/biomass peaked in September followed by a decline, reaching very low values (<4 individuals m^{-2} and 3 g biomass m^{-2}) during March–May period in all land use types except TAFS showing density of 11–30 individuals m^{-2} and biomass of 20–55 g m^{-2} at this time of the year. TAFS supported larger density and biomass compared to TPCS in all months except July when the latter showed marginally larger values compared to the former (Fig. 2a and b, Table 4).

In the peak month of September, total density showed a trend of TAFS > TPCS > MDNF > RAL > AAL > RFL > HDNF (147, 132, 63, 27, 14, 8 and 5 individuals m^{-2}, respectively) and biomass of TAFS > TPCS > MDNF > RFL > RAL > AAL > HDNF (266, 199, 51, 24, 21, 16, 11 g m^{-2}, respectively). Total earthworm density over the year (i.e., sum of observations of all months shown in Fig. 2a and b) showed a trend of TAFS (358 individuals m^{-2}), TPCS (263 individuals m^{-2}) > MDNF (97 individuals m^{-2}) > RAL (53 individuals m^{-2}) > RFL (28 individuals m^{-2}) > AAL (25 individuals m^{-2}) > HDNF (7 individuals m^{-2}) and biomass of TAFS (663 g m^{-2}) > TPCS (404 g m^{-2}) > MDNF (79 g m^{-2}) > RFL (63 g m^{-2}) > RAL (45 g m^{-2}) > AAL (27 g m^{-2}) > HDNF (15 g m^{-2}). Thus, total earthworm density in MDNF was 2.7–3.7-fold and biomass 5.1–8.4-fold lower as compared to TPCS and TAFS. A change from TPCS to TAFS followed 1.4- and 1.6-fold increase in total density and biomass, respectively, and from MDNF to HDNF 11- and 4-fold decline, respectively. Rehabilitation of HDNF improved earthworm abundance but total density and biomass in RFL remained 3.6- and 1.3-fold, respectively, lower compared to MDNF. Abandonment of TPCS resulted in more than 10-fold decline in total earthworm density and 15-fold decline in biomass. Earthworm abundance increased following rehabilitation but earthworm density and biomass in RAL remained 5- and 9-fold, respectively, lower compared to TPCS.

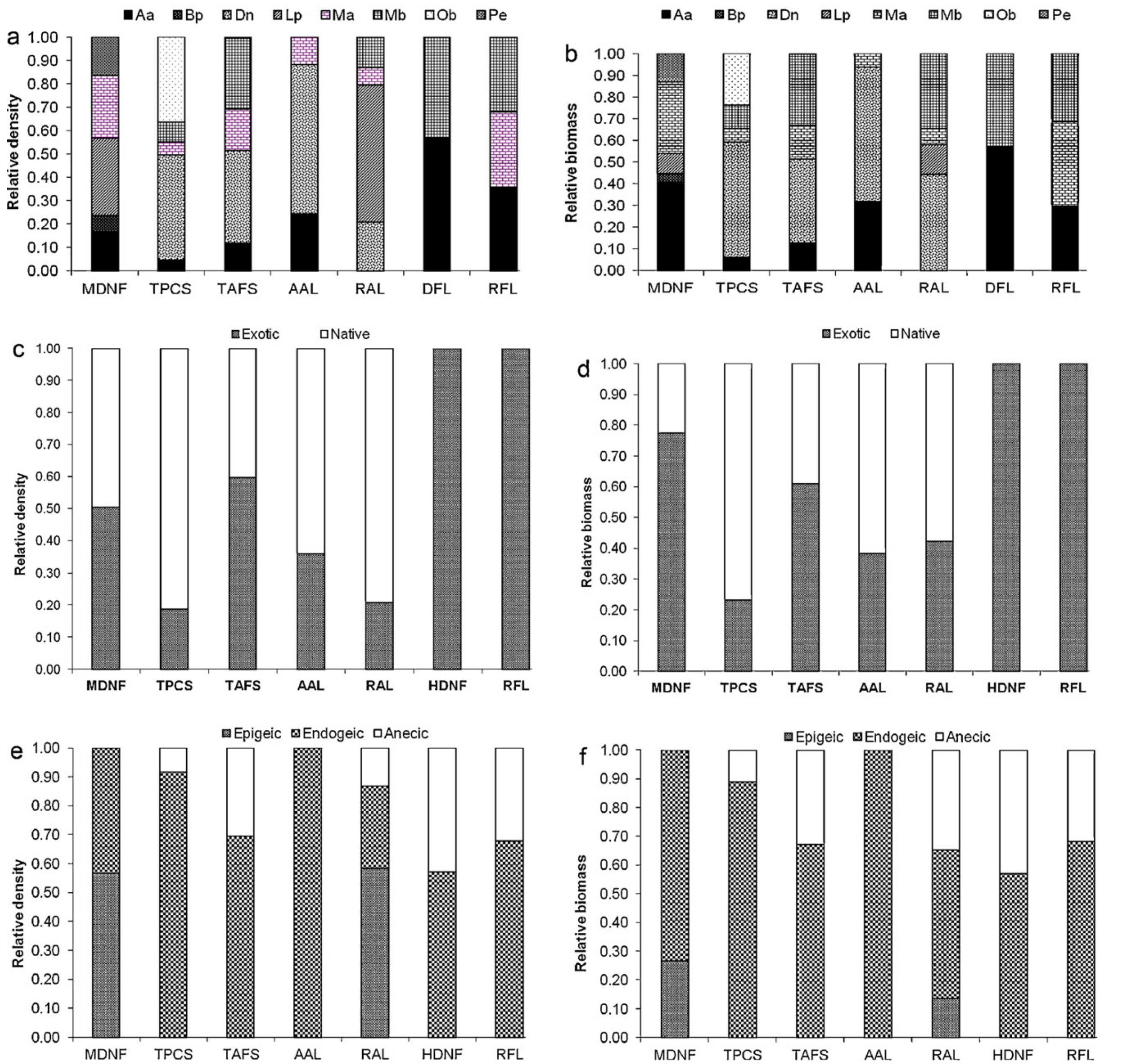

Fig. 3. (a–f) Relative density/biomass of different taxonomic species (a, b), biogeographic groups (native/exotic) (c, d) and functional groups (endogeic, epigeic and anecic) (e, f) in different land use types in Bhiri-Banswara village landscape, Central Himalaya, India. MDNF, Moderately degraded natural forests; TPCS, Traditional pure crop system; TAS, Traditional agroforestry system; AAL, Abandoned agricultural land; RAL, Rehabilitated agricultural land; HDNF, Highly degraded natural forest; RFL, Rehabilitated forest land; Aa, *Amynthas alexandri*; Bp, *Bimastos parvus*; Dn, *Drawida nepalensis*; Lp, *Lennogaster pusilla*; Ma, *Metaphire anomala*; Mb, *Metaphire birmanica*; Ob, *Octochaetona Beatrix*; Pe, *Perionyx excavatus*.

Relative abundance of different species and their aggregation by nativity and functional guilds is shown in Fig. 3a–f. Apart from absence of *P. excavatus* and *B. parvus* and presence of *O. beatrix*, *D. nepalensis* and *M. birmanica*, traditional cultivated lands (TPCS and TAFS) had lower relative abundance of *A. alexandri* and *M. anomala* compared to MDNF. A change from TPCS to TAFS followed a substantial increase in relative abundance of *A. alexandri*, *M. anomala* and *M. birmanica* at the expense of decline of that of *O. beatrix* and *D. nepalensis*. *A. alexandri*, a species common to MDNF and HDNF, contributed around 50% of total density and biomass in the latter compared to 15% of density and 40% of biomass in the former. Abandonment of TPCS was associated with an increase and rehabilitation with a decrease of relative abundance of *D. nepalensis*. Forest rehabilitation reduced relative dominance of *M. birmanica* (Fig. 3a and b).

Native peregrines were altogether absent in HDNF and RFL. Conversion of MDNF to HDNF resulted in replacement of exotic *M. anomala* by *M. birmanica* and loss of two native peregrine species (*L. pusilla* and *P. excavatus*) and one exotic species (*B. parvus*), while rehabilitation of HDNF could recover only *M. anomala*. Abandonment of TPCS followed loss of one native peregrine and one exotic species, while rehabilitation followed replacement of the exotic *A. alexandri* by *M. birmanica* alongwith colonization of native peregrine *L. pusilla* (Fig. 1). Land use had significant ($P < 0.05$) effect on pooled density/biomass of natives and exotics wherever they coexisted. Exotics accounted for 50–60% of total density and 62–77% of total biomass in MDNF and TAFS compared to 18–35% of density and 21–40% of biomass in TPCS, AAL and RAL. A change from TPCS to TAFS followed a drastic increase in relative dominance of exotics. Rehabilitation of agricultural land was associated with an increase in relative density but negligible change in relative biomass of exotics (Fig. 3c and d).

Earthworm community of AAL comprised only one functional group (endogeics), RAL all the three groups and other land use types only two groups. Epigeic species were present only in MDNF and RAL, contributing around 50% of total density in both land use types and 25% of total biomass in MDNF and 15% in RAL. A change from TPCS to TAFS was associated with a decline in relative density/biomass of endogeics by 20% and from HDNF to RFL with an increase by 10%. Endogeics dominated over anecics in land use types where these two groups coexisted (Fig. 3e and f).

3.5. Soil physico-chemical properties and earthworm density/biomass

Of all soil physico-chemical properties analysed, only SOC was significantly related to total earthworm density and biomass. SOC (x) explained 68% variation in total density (y) ($y = 0.0023 \times ^{4.06}$; $R^2 = 0.68$) and 63% variation in total biomass (y) ($y = 0.0049 \times ^{3.90}$; $R^2 = 0.63$).

4. Discussion

4.1. Species richness

Earthworm species richness in Bhiri-Banswara landscape (8 species) is within the range of reported local richness 5–12 species (Lavelle and Spain, 2001; Sinha et al., 2003; Dlamini and Haynes, 2004; Whalen, 2004; Decaens et al., 2008; Geissen et al., 2009). Species richness and community structure within a land use, however, is highly variable, with 1–5 species reported in cultivated lands and 3–8 species in forests in the past studies in the Central Himalaya (Kaushal and Bisht, 1994; Kaushal et al., 1995; Sinha et al., 2003; Bhadauria et al., 1997, 2000) compared to 5 species in both land use types in the present study. Local species richness of Bhiri-Banswara landscape (8 species) is fairly low compared to 48 species constituting the regional pool (Julka and Paliwal, 2005), as also noted elsewhere (Sinha et al., 2003; Geissen et al., 2009), because of patchy distribution of a large number of species arising from huge variations in local climatic/edaphic conditions, land use history and management practices within Central Himalaya and high levels of competition in earthworm communities limiting alpha diversity to a low species number whatever the level of beta diversity (Decaens et al., 2008). *Metaphire anomala* and *M. birmanica* occurring in cultivated lands/forests were not found in similar land use types in Central Himalaya analysed in the past (Kaushal and Bisht, 1994; Kaushal et al., 1995; Sinha et al., 2003; Bhadauria et al., 1997, 2000), while *Allobophora* and *Eutyphoeus* reported in the past studies were not found in this study. Species richness (5 species) in the present age-old traditional organic farms is higher compared to 2–3 species observed in more recent conventional organic farms by Whalen et al. (1998) but much lower than the ones studied by (Pfiffner and Luka, 2007) in developed countries. This study does not support the generalization that forests may represent biodiversity 'hot spots' in agricultural landscapes (Hagvar, 1998). This generalization is perhaps more likely to hold true where forests are relatively intact, agriculture is intensive, with high rates of inputs of agrochemicals and intensive tillage, and the two land uses are isolated unlike the present one where forests are perturbed since long, agrochemicals are not used at all and agricultural and forest land use are interlinked production systems.

There are inherent problems with sampling in order to make accurate assessments of size and structure of earthworm communities, since the techniques used must be invasive to the earthworms' natural environment (Lawrence and Bowers, 2002; Bartlett et al., 2006). Sampling worms by hand sorting of soil monoliths of size 25 cm × 25 cm × 30 cm may be considered an efficient method in the Central Himalayan region where soils are shallow and worms inhabiting deeper soils (>25 cm) and/or of larger size (>20 cm) are not observed (Kaushal and Bisht, 1994; Kaushal et al., 1995; Sinha et al., 2003; Bhadauria et al., 1997, 2000; Julka and Paliwal, 2005). Use of irritants and larger quadrants would be required for efficient sampling of worms of large size and the ones inhabiting deeper soils.

4.2. Native vs exotic species

Loss of native species and/or success of exotic species are often associated with intense disturbances of primary forests and land use intensification (Lavelle et al., 1987; Barros et al., 2003; Negrete-Yankelevich et al., 2007; Geissen et al., 2009). Nevertheless, coexistence of native and exotic species is a more common trend than absolute exclusion of natives in disturbed ecosystems (Callahan and Brail, 1999; Brown et al., 2004; Dlamini and Haynes, 2004; Riggins et al., 2009; Marichal et al., 2010). Exotics do survive in little disturbed primary forests (Dlamini and Haynes, 2004; Hendrix et al., 2006). All species in the present case were peregrine possibly because of mass extermination of native endemic species due to glaciation in the Himalaya (Julka and Paliwal, 2005). None of the native peregrine species could survive in highly degraded natural forests (HDNF) and abandoned agricultural land (AAL) subject to intense-persistent disturbances. Native *D. nepalensis* could not survive in moderately disturbed natural forests (MDNF). Colonization by exotic *M. birmanica* in rehabilitated forest land (RFL) and by native *L. pusilla* in rehabilitated agricultural land (RAL) reflects importance of neighbouring ecosystems in development of earthworm communities in degraded ecosystems (Thomas et al., 2004). Further studies are needed to gain a better understanding of processes determining development of earthworm communities following rehabilitation of degraded ecosystems. Species composition under tree plantations could be similar to that under native forests (Fragoso et al., 1999) but a period of 20 years of rehabilitation is perhaps too short for stabilization of earthworm community structure and composition (Folgarait et al., 2003).

4.3. Seasonality

The highest hatches were in monsoon, with lower numbers in winter and a drastic reduction in summer. In general, all species hatch during early monsoon, grow to adulthood over the monsoon period and decline in dry winter and summer largely due to adverse temperature/moisture conditions. Larger populations during wet season compared to dry seasons have been reported in previous studies in the Himalaya (Kaushal and Bisht, 1994; Bhadauria et al., 1997; Sinha et al., 2003) and elsewhere (Brown et al., 2004; Rossi and Blanchart, 2005; Sileshi and Mafongoya, 2006; Pauli et al., 2011).

4.4. Earthworm abundance in relation to land use, soil properties and disturbances

The results presented do not reflect the trends of land use intensification resulting in decline in SOC, earthworm species richness and abundance observed in situations characterized by recent and drastic ecological changes (e.g., conversion of primary forests/old secondary forests to croplands/pastures/plantations/seral vegetation, intensive use of agrochemicals and replacement of native plant species by exotic species in pasture) and negligible flows of resources among land use types differentiated in the landscape (Blair et al., 1995; Fragoso et al., 1997; Whalen et al., 1998; Decaens et al., 2004; Lemenih et al., 2005; Sangha et al., 2005; Collard and Zammit, 2006; Smith et al., 2008). Bhiri-Banswara village landscape, like many other landscapes in Indian Himalaya (Maikhuri et al., 2000; Semwal et al., 2004), has quite a stable land use, with huge amounts of organic matter/nutrients from forests and abandoned agricultural land transferred to agroecosystems in the form of farm yard manure (i.e., leaf litter-livestock excreta mixture). Crop–livestock–forest–human interactions are such that abandoned agricultural land (AAL) and highly degraded natural forests (HDNF) have similar SOC levels and forest soils have SOC levels equal to that in the traditional pure crop system (TPCS) and lower than that in traditional agroforestry system (TAFS) (Kundu et al., 2007; Singh et al., 2008). Lopping of trees, litter removal, grazing and silvicultural practices favouring dominance of oak tend to reduce niche heterogeneity as well as food availability limiting earthworm diversity and abundance in forests (Lee, 1985; Edwards et al., 1995; Smith et al., 2008). However, temporal separation (litter removal in winter and lopping in summer) coupled with mild intensities of disturbances (removal of only around 60% of annual litter fall, lopping of <40% branches and regulated low intensity grazing) enable survival of epigeic *Perionyx excavatus*, *Bimastos parvus* and *Lennogaster pusilla* in moderately degraded natural forests (MDNF). These epigeic species fail to survive in traditional pure crop and agroforestry systems in the absence of surface litter (Fragoso and Lavelle, 1992; Lagerlof et al., 2002) arising from low litter fall rates (due to low tree density, small tree size and intense lopping) and incorporation of surface residues in soil by ploughing. Yet, ploughing in dry months (when adult population in plough layer is quite low), better soil moisture conditions on terraces, incorporation of huge amount of organic manure/crop residues and niche heterogeneity arising from crop diversification maintain earthworm species richness equal to and density/biomass higher than that in forests.

A significant positive relationship between earthworm abundance and SOC indicates the latter to be a limiting factor (Pashanasi et al., 1992; Gonzalez and Zou, 1999). Since only 63–68% of variation in total earthworm density/biomass could be explained by total SOC, there is a need of further studies taking into account other factors related to the nature of each land use system, e.g., soil temperature, moisture and chemical quality of organic inputs and soil organic matter (Edwards and Bohlen, 1996; Zaller and Arnone, 1999; Mboukou-Kimbatsa et al., 2007; Leroy et al., 2008), landscape structure and processes, e.g., dispersal of earthworms between land use systems by movement of cattle, transplantation of seedlings and location of different agricultural plots towards the lower and forests towards the upper regions of hill slopes, and species-specific attributes, e.g., dispersal, colonizing and competitive abilities, soil/food preferences, exposure to predators and reproductive strategies (Decaens and Jiménez, 2002; King and With, 2002; Lavelle and Spain, 2001; Thomas et al., 2004; Smith et al., 2008) influencing earthworm community structure and abundance.

Traditional farmers in Bhiri-Banswara landscape maintain SOC levels (13–18 $g\,kg^{-1}$) much higher than the threshold of 7.5 $g\,kg^{-1}$ for highly fertile soil in Indian agriculture (Prasad et al., 2003). There are so far no scientific criteria of evaluating soil quality based on earthworms in India as also in many other countries. The present traditional agroecosystems have earthworm density and biomass much in excess of the limits (80–120 individuals m^{-2}; 60–100 $g\,m^{-2}$ biomass) considered to indicate 'good agricultural practice' in some developed countries (Pfiffner and Luka, 2007) and comparable to biomass observed in some of the scientifically designed modern organic agricultural systems (Whalen et al., 1998; Schmidt et al., 2003) but lower than the extreme values of 400 $g\,m^{-2}$ reported in tropical pastures (Decaens et al., 2004). The highest level of SOC in the present landscape (18 $g\,kg^{-1}$) is far lower than the levels (>130 $g\,kg^{-1}$) at which factors other than SOC become limiting (Li et al., 2010). Earthworm biomass in peak season in traditional agriculture (199–266 $g\,m^{-2}$ in September) is much higher than the values in the range of 1–99 $g\,m^{-2}$ reported in past studies in Central Himalaya (Kaushal et al., 1995; Bhadauria et al., 1997; Sinha et al., 2003) reflecting huge variation in factors determining earthworm abundance/growth within traditional farming system in the region. Earthworm biomass in peak season in moderately degraded natural forests (51 $g\,m^{-2}$) was higher and other uncultivated sites (11–24 $g\,m^{-2}$) lower than the threshold of 30 $g\,m^{-2}$ at/above which earthworms have positive effects on primary production (Brown et al., 2004).

5. Conclusions

This study shows a significant effect of land use on earthworm populations in a typical traditional village landscape of Central Himalaya characterized by a relatively stable land use and transfer of a sizeable amount of organic matter/nutrients from forests to agricultural land in the form of farmyard manure. Relatively less disturbed forests and traditional agricultural land uses resemble in terms of earthworm species richness but not species composition. Thus, heterogenous village landscape mosaics are likely to have higher earthworm diversity than more homogenous forest cover in protected areas where agriculture is banned. Indigenous agroforestry innovation improves earthworm abundance but not species richness. Indigenous pure crop or agroforestry system are markedly rich in earthworm fauna but their abandonment follows depletion of earthworms, more so of native peregrine species, as well as soil organic carbon. Similar trends also follow intense forest degradation set in by logging followed by unregulated use of forest resources. The present strategies of rehabilitation are unable to recover earthworm communities in totality over a period of 20 years. However, huge variability in land use histories, management practices and biophysical conditions warrant more research on spatio-temporal dynamics of earthworm communities and the linkages between belowground biodiversity, aboveground biodiversity and ecosystem functions.

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