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Conservation and Sustainable Management of Belowground Biodiversity: A Review on the Functional Role of Soil Fauna in Indian Ecosystems with Particular Reference to Earthworms

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ABSTRACT

Biodiversity is one of the most important areas of environmental research, management and concerns. Our understanding about belowground biodiversity and its functions is not as strong as that on aboveground biodiversity. This paper presents a review of the existing knowledge on soil fauna, with particular reference to (i) community structure, biomass and population turnover in different land uses; (ii) bioturbation activity; (iii) soil fauna – soil micro-flora interaction; (iv) role of soil fauna in land reclamation; and (v) vermitechnology. Based on the existing knowledge, the areas of future research for conservation and management of below ground biodiversity have been identified.

Key Words: Soil fauna, Earthworms, Land uses, Vermitechnology.

INTRODUCTION

A number of scientists in Europe (Hansen 1877, Muller 1978, Darwin 1881, Unquhart 1887) by their observations believed that earthworms played a beneficial role in soil formation and maintenance of soil fertility. Aristotle called earthworms as 'Earth entrails' (or intestines), probably because they lived in soil, churning it up (Kevan 1985). Darwin (1838 and 1881) drew attention to the role of earthworms in the breakdown of forest litter, burial of litter lying on surface soil and in maintenance of soil structure, aeration and fertility. Darwin described how earthworms through their feeding activities and mixing of organic materials and soil minerals produce "vegetable mould". Even after the publication of Darwin's book, many people viewed earthworms as a pest of crops (Feller et al. 2000). However, some beneficial uses of earthworms such as fish bait, medicinal value and food for some native American Indians were recognized. Thus, importance of earthworms in maintenance of soil fertility was not realized much until Darwin published his observations during 1880s, although Gilbert White (1789), Hansen (1877) and Muller (1978) recorded their observations on the role of earthworms in the formation of soil humus.

Until 1950 (Kuhnelt 1950), not much work was done on soil faunal activities Satchell (1967 and 1983) highlighted the contributions of earthworms to nitrogen excretion, mucous production and biomass turnover in European forests. Later, role of earthworms in maintaining higher plant productivity was demonstrated in pot experiments using many crops (Edwards and Lofty 1977, Lavelle 1988).

Comprehensive taxonomic and distributional survey of Oligochaetes, particularly of earthworms, was done by Stepheson (1923). This work is now obsolete due to nomenclatural changes and discovery of new taxonomic characters. The recent publication of Julka (1988, Julka and Paliwal, 2005) fills the much needed gap in taxonomic and distributional studies which can be taken as the most recent comprehensive publication on the taxonomy of Indian earthworms. Many Indian workers (Dutt 1948, Joshi and Kelkar 1952, Nijahwan and Kanwar 1952, Khambata and Bhatt 1957, Bhatt et al, 1960) evaluated the role of earthworm's soil aggregation and maintenance of soil fertility. Earthworms were considered as pests in tobacco nursery and soapnut was used to control them (Patel and Patel 1960). Bahl (1945, 1947) studied body structure and physiology of nephridial excretion, while Saroja (1959) worked on respiratory metabolism of earthworms.

No comprehensive effort was done in India to understand the life cycle pattern, population dynamics and functional role of earthworms in Indian ecosystems until the studies of Dash et al. (1974), Dash and Patra (1977 and 1979), Dash (1978), Kale and Krishnamoorthy (1978 and 1981), Senapati and Dash (1979), Dash and Senapati (1980), Senapati and Dash (1984) and Mishra and Dash (1984). These studies dealt with life cycle patterns, species diversity and composition of earthworm communities, functional role of earthworms with regard to worm-cast production, nitrogen excretion, secondary productivity and energetics. Efforts were also made to investigate the interaction of earthworms with soil microflora and nematodes (Dash et al. 1979, 1980, 1984 and 1986), potential uses of earthworms as feed material for poultry and as a catylytic agent for edible mushroom production (Das and Dash 1989, Dash and Das 1989, 1990) and the process of vermicomposting (Dash and Senapati 1982 and 1985, Kale et al. 1982, Dash et al. 1984, 1985 and 1986). Although the work was not funded by International Biological Programme (IBP), these studies were influenced by their philosophy.

The recent studies on earthworms are centered on their role in nutrient cycling, waste land reclamation, crop productivity, species distribution in relation to land uses, and vermicomposting (Kale and Krishnamoorthy 1981, Sahu et al. 1988, Reddy and Reddy 1987, 1990 and 1993, Sahu and Senapati 1991, Bhadauria and Ramakrishnan 1989, 1991 and 1997, Bhadauria et al. 2000, Singh 1991 and 1997, Dash 1994 and 1999, Senapati 1993, Ismail 1990 and 1997, Lavelle et al. 1996, Choudhuri and Bhattacharjee 2002, Chaudhuri et al. 2003, Bhattachajee and Chaudhuri 2002, Manna et al. 1997, Gajalaxmi et al. 2001, Sinha et al. 2003, Tripathi and Bhardwaj 2004, Kale and Dinesh 2005, Maikhuri et al. 2005 and 2008). These studies have accumulated wealth of knowledge on population biology and functional role of earthworms in India, suggesting that earthworms are the most important soil macrofauna.

This paper provides a review of knowledge, with special reference to India, on (i) community structure, biomass and population turnover in different land uses; (ii) bioturbation activity; (iii) soil fauna – soil microflora interaction; (iv) role of soil fauna in land reclamation; and (v) vermitechnology..

EARTHWORM RESOURCE OF INDIA

Table 1 provides information on earthworm resources in the three major ecoregions of India, viz., Himalaya, Indo-Gangetic plains and Deccan peninsula including Western Ghats (Julka 1988, Julka and Paliwal, 2005). The Deccan peninsula is highly rich in earthworm fauna and harbours many epigeic and anecic species such as *Dichogaster bolaui, Drawida willsi, Perionyx excavatus, Perionyx sansibaricus, Ramiella* sp. and *Lampito mauritii* valued for their use in vermitechnology (Dash and Senapati 1985, Dash 1999). The North-East and Western Himalayan regions are also rich in many endemic (native) species e.g., *Octochaetona beatrix, Eutyphoeus festivus, E. nanianus, E. waltoni* and some *Drawida* species and exotic species e.g., *Octolasion tyrtaeum, Amynthas cortices* and *Bimostus parvus* (Bhadauria and Ramakrishnan 1989 and 1991, Bhadauria et al. 2000, Sinha et al. 2003).

Distinct taxonomic groups of earthworms have evolved on every continent except Antarctica. Through human movement and transport system many species native to Europe, Africa and America are now found in almost all settled regions of the world (Jamieson 1978, Reynolds and Cook 1976). Nine families with 69 genera and more than 418 species have been described from India (Julka and Paliwal, 2005). The species of the family Octochaetidae is the most frequent family (30 genera) found in Indian ecosystems. Endemic species of *Eutyphoeus* is widespread in alluvial soils of the Indogangetic plains and *Haplochaetella spp* in laterite and red soils of the Western Ghats. The Peninsular plateau houses many peregrine species. The similarity indices of earthworm communities in different land-uses in the state of Karnataka in south India indicate that the species composition of natural forests is closer to that of coffee, *Acacia* and cardamom plantations and paddy fields. Grasslands showed least similarity with other land-uses. However *Pontoscolex corethrurus*, an endogeic species, was found in all land-uses (Kale et al. 2008, Chandrashekara et al. 2008). Earlier studies by Dash and Patra (1977), Senapati and Dash (1981), Mishra and Dash (1984) and Senapati (1993) showed that the

Table 1. Earthworm resources in India*
Total number of species 418 (including 44 exotic species) in 69 genera and 9 families (Julka and Paliwal 2005)

Family	Genera	Number of species*	Himalaya		Indo-Gangetic Plain	DeccanPennisula and Western Ghats
			East	West/Central		
Acanthodrilidae	Microscolex	1	Exotic			
	Pontodrilus	1	Exotic			
	Plutellus	22	Peregrine			
Almidae	Criodrilus	1	Exotic			
	Glyphidrilus	4	+	+	+	+
Eudrilidae	Eudrilus	1	Native to Ethiopian region, exotic in India (Poona**)			
Glossoscolecidae	Pontoscolex	1	Exotic species			
Lumbricidae	Allolobophora	2	The whole family is exotic to India			
	Aporrectodea	3				
	Dendrobaena	2				
	Dendrodrilus	1				
	Eisenia	1				
	Eiseniella	1				
	Lumbricus	3				
	Octolasion	2				
Megascolecidae	Amynthus	11	Peregrine			
	Comarodrilus	1				
	Kanchuria	4				
	Lampito	8	L. mauritii is widely distributed			
	Megascolex	33	Peregrine			
	Metaphire	10	Peregrine			
	Nelloscolex	1	+			
	Notoscolex	11				
	Perionyx	46	widel distributed			
	Pithemera	1	Peregrine			
	Polypheretima	2				
	Tonoscolex	7	+			
	Troyia	1	+			
Moniligastridae	Desmogaster	1	Peregrine			
	Drawida	8	+	+	+	+
	Moniligaster	10	Peregrine			
Ocnerodrilidae	Curgionia	1				
	Deccania	1				
	Eukerria	1				
	Gordiodrilus	1	Peregrine			
	Malbarica	5			+	
	Nematogenia	1				
	Ocnerodrilus	1	+		+	
	Thatonia	5			+	
Octochaetidae	Bahlia	1			+	
	Barogaster	3				
	Calebiella	1				
	Celeriella	7				

Table 1. (Continued)

Family	Genera	Number of species*	Himalaya East	Himalaya West/Central	Indo-Gangetic Plain	DeccanPennisula and Western Ghats
	Chaetocotoides	1			+	
	Dashiella	1			+	
	Dichogaster	5	Peregrine			
	Eudichogaster	6		+	+	
	Eutyphoeus	22	Peregrine			
	Hoplochaetella	19	+		+	+
	Herbettodrilus	1				+
	Karmiella	2				+
	Konkardrilus	6				+
	Kotegeharia	1				+
	Lennogaster	7				+
	Mallehula	1			+	+
	Octochaetona	15		+	+	+
	Octonochaeta	1			+	+
	Octochaetoides	1			+(?)	+
	Parryiodrilus	1			+(?)	+
	Pellogaster	3				+
	Priodochaeta	1				+
	Priodoscolex	1				+
	Ramiella	5			+	+
	Rillogaster	2	+			+
	Scolioscolides	1				+
	Senapatiella	3				+
	Schimodrilus	2				+
	Travoscolides	4				+
	Wahoscoles	10				+
	Incerte sedis	7				+

* based on personal communication from J.M. Julka; ** personal communication from B.K. Senapati

pastures and mixed wood forests differed in Orissa in terms of earthworm species composition although *Lampito mauritii* was found in all land-uses. Studies in village landscapes in Himalayan region in north India (Kaushal and Bisht 1994, Bhadauria et al. 2000, Sinha et al. 2003) showed occurrence of three species in pasture soils compared to seven to eight species in other land-uses. *Amynthas* sp. is common in these sites. Biological invasion was observed in both early successional and climax forest ecosystems. However, information on earthworm distribution and community structure in central and western part of India is scanty.

Population Density, Biomass and Turnover

Data available on earthworm population density, biomass and turn over (annual secondary production to average biomass) in different regions of India is given in Table 2. In grasslands earthworm density may be as high as 14 million ha^{-1}, except in a cropland at Ranchi where the peak density of a single species population reached about 26 million ha^{-1}. The density is comparable in pasture and crop fields and forest soils of many sites in India (Table 2). However, the density of earthworms in different land-uses in Nilgiri Biosphere

Reserve in Kerala is less in comparison to other sites in India. Two to eight species of earthworms have so far been recorded in any particular site. The density of earthworms in different sites depends upon soil temperature, moisture, pH, litter and soil organic carbon and root biomass. Highest population density has been found in pastures - grasslands during monsoon period in Karnataka, Orissa and Central Himalayan region (Table 2). In Nanda Devi Biosphere Reserve earthworms occurred in higher numbers at lower elevations, especially in agriculture land-uses during monsoon season and in oak forests during post-monsoon period. At higher elevations earthworms were found in agricultural land-uses but not in alpine pastures and *Cedrus* forests. Earthworms were sampled from Home gardens and areas under medicinal plant cultivation in both monsoon and post-monsoon period at all elevations (Maikhuri et al. 2005 and 2008). Further, in Nanda Devi Biosphere Reserve, density of worms in rainfed agricultural land was higher than that in irrigated land. In Nilgiri Biosphere Reserve in Kerala, 14 species of earthworms were recorded in different land-uses. The earthworm community consisted of epigeic, anecic and endogeic species. Occurrence of endogeic species, *Parryodrilus lavelee* and *Pontoscolex corethrurus* in almost all land-uses, with density varying from 2 m^{-2} in degraded ecosystems to 294 m^{-2} in mixed perennial plantations and deciduous forests, suggests that these species may be suitable for restoration of soil fertility in degraded lands (Chandrashekara et al. 2008). In most studies, population size has been estimated in terms of numerical abundance and not in terms of biomass. However, the average biomass value varies from about 252 kg ha^{-1} to 780 kg ha^{-1} with an annual turn-over varying from about one to five in pasture and forest sites in Orissa (Table 2). The biomass data however, are comparable to many sites across the world (Dash 1999).

Earthworm cocoon morphology and seasonal dynamics of cocoons and juveniles in tropical pasture soils in Orissa (Senapati and Dash 1979, Dash and Senapati 1980) and in Karnataka (Kale et al. 2008) indicate that in most of the species cocoon production occurs in later period of monsoon/post-monsoon period with peak emergence from October to January. Cocoons are found in very small numbers in summer Dash and Senapati (1980 and 1982) have reported that Indian Megascolecoids required temperatures of about 20^{o}C and soil moisture of >7% for reproduction. The maximum population size in North-East has been observed in wet season except some species peaking in winter (Bhadauria and Ramakrishnan 1989). Studies carried out in some African sites (Lavelle 1983) indicate peak cocoon production in the dry spell at the end of each wet season. Extensive studies on cocoon dynamics in other Indian sites are required for drawing generalizations about earthworm population structure and dynamics in Indian conditions.

Secondary Productivity and Energetics of Earthworm Community

In the 1960s and 1970s, the International Biological Programme (IBP) boosted research on soil biology and ecology around the world. In these studies great importance was given to measure community metabolism, energy flow, nutrient cycling and primary and secondary productivities of different biomes (Phillipson 1971, Coupland 1979, Breymeyer and Van Dyne 1980). In these studies some data on the role of soil fauna, especially of macrofauna including earthworms, were generated. The secondary production in many species varies seasonally and with climatic extremes. Production: Respiration ratio (P/R ratio) is highest for soil animals in the tropical rangelands and in the polar region (Dash 1999). In these extreme climatic conditions, more energy is stored in secondary production to withstand adverse environmental conditions. The relative amount of energy allocated to growth and reproduction have been calculated for a few species. Energy production of about 56.02 kcal m^{-2} yr^{-1} for *Lumbricus terrestris* populations in Europe was reported by Lakhani and Satchell (1970) and Satchell (1971), 16.80 kcal m^{-2} yr^{-1} for *Millsonia anomala* in Lamto savanna, Ivory Coast by Lavelle (1977 and 1983) and 58.02 kcal m^{-2} yr^{-1} and 12.03 kcal m^{-2} yr^{-1} from a partly protected and grazed pastures respectively, by Nowak (1975).

In Indian pastures, Senapati and Dash (1981) reported 122.05 kcal m^{-2} yr^{-1} -144.06 kcal m^{-2} yr^{-1} of secondary production by earthworms. Average P/B ratio for earthworms is 2.4 to 4.5 for ungrazed and grazed pastures, respectively, in India (Dash et al.1974, Senapati and Dash 1981) in comparison to the ratio of 1.2 to 2.6 in Lamto savanna (Lavelle 1977) and 0.9 to 1.3 in temperate climate of Europe (Nowak 1975).

In tropical pastures of India, the secondary production of earthworms was about 5% and 3% of the net primary production in grazed and ungrazed pastures, respectively. Further, tissue growth amounted to 95% and cocoon production to 5% of secondary production of the earthworms. About 25% of the total

Diversity Two Species

Table 2 [illegible] rice field,

Table 2 (Continued)

Land use/ecosystem	Pasture, Kumaon Himalaya	Cultivated soils, Varanasi, Uttar Pradesh	Village landscape, Central Himalaya	Cropland, Pasture, Garbage sites	Village landscape, Garhwal Himalaya

Diversity

Three species (*Amynt*

Table 2. (Continued)

Land use/ecosystems

Nanda Devi Biosphere Reserve,

ntral Himalaya

Nilgiri Biosphere Reserve, Kerala

Diversity

Eigh

1. Das

energy assimilated by earthworms was stored in body tissue and 2% in cocoon production. The growth rate of earthworms is a function of age and body size in a particular ecosystem and it was estimated to be generally 10 mg g^{-1} body weight day^{-1} and 7mg g^{-1} body weight day^{-1}, respectively, for worms weighing < 150 mg and 200-700 mg during the rainy season (Dash 1987). Several factors like food, temperature, habitat conditions, species and life cycle pattern influence growth and activity of earthworms. Since earthworm populations account for about 80 % of the total soil faunal biomass in tropical pastures, it has been estimated that secondary production of soil fauna may account for 7-10 % of the net primary production in tropical pastures (Dash 1999). However, limited research work on secondary production in Indian ecosystems remains a constraint in making generalizations. Total assimilation, energy spent in respiration, mucous production and energy stored in tissue growth are the most commonly measured parameters in studies carried out on earthworm energetics and reproduction. Considering these aspects only, the energy flow in earthworm community and also the total faunal community have not been found to be more than 15-20% of the total energy flow in the decomposer system in tropical sites in Orissa and temperate sites in Europe (Dash et al.1974, Petersen and Luxton 1982, Dash 1999). However, soil biologists generally agree that this is partially true (Huhta 2007). Contribution of soil fauna to decomposition through their own metabolism is seemingly much less than their role in stimulation of decomposition by microbes. Earthworms being the most dominant component of soil fauna in terms of biomass make a significant contribution to the stimulation of soil microbial activity (Dash et al. 1985, Lavelle 1988).

In tropical grasslands in the state of Orissa, the oxygen consumed through metabolism by earthworm community amounted to about 1200-1440 kJ m^{-2} of energy (mg O_2 m^{-2} (converted to equivalent energy values, Engelmann 1961, Golley 1961). The annual energy output in mucous production amounted to 570-2380 kJ m^{-2} and annual production of earthworm tissue to 500-700 kJ m^{-2} (Dash and Patra1977, Senapati and Dash1981 and 1983). The earthworm community utilized about 13% to 16% of the net primary production in grasslands estimated on the basis of only the assimilated energy (Dash 1987). These studies indicate that the P/B ratio is about 25% and Respiration/Assimilation ratio about 75%. This type of study has not been done in other land-uses in India and hence comparison is not possible. Senapati (1994) has worked on the energy budget of an epigeic earthworm, *Drawida bolaui* (adult size about 4 cm), a vermicomposting species and, *Polypheretima elongata* (adult 50 cm), an endogeic species. The epigeic worm utilizes 2.5 kJ g^{-1} body weight day^{-1} compared to only 0.6 kJ g^{-1} body weight day^{-1} by the endogeic species. Studies on energetics using earthworms as a tool for land-use management and waste land reclamation are scanty.

Bioturbation Activity by Earthworms

Earthworms drag leaves into their burrows, degrade litter, feed on fragments (Darwin 1881) and bring large amount of soil from deeper layers to the surface by depositing castings. The amount of litter burial in burrows and amount of soil turn over depends upon type of litter, soil, geographical region and earthworm species i.e., epigeic, anecic and endogeic. Litter bag studies done in Europe and North America (Kurcheva 1960, Crossley and Witkamp 1964, Dash and Cragg 1972, Standen 1978) have established the role of soil fauna in the breaking down of litter. Decomposition process and the weight loss of litter mass in litter bags with free access to earthworms is 2.5 times faster than that in bags restricting access (Kurcheva 1960, Edwards and Heath 1963, Witkamp and Crossley 1966). The litterbag studies are useful to measure the disappearance and comminution of litter but not the rate of decomposition. However these studies are still popular (Vedder et al. 1996, Heneghan et al. 1999, Kandeler et al. 1999) and provide valuable information. Earthworms play an important role in the initial process of leaf litter fragmentation. Earthworms have been found to consume leaf litter more than the consumption by all other soil invertebrates taken together in European temperate forest ecosystems (Edwards and Heath 1963). The rate of breakdown of litter depends upon the type of litter (Raw, 1959). Litter feeding earthworms like *Lumbricus castaneus* and *Eisenia foetida* produce casts rich in fragmented leaf litter. In temperate deciduous woodlands in Europe, 3 Mg ha^{-1} of leaf litter produced in a year is expected to be fully consumed by the worms in 3 months only (27 g of litter consumed by earthworm day^{-1}). Some studies on habitat preference of earthworms (Singh 1997), gut loading and feeding rate (Dash et al. 1984 and 1986) and litter consumption (Kale and Krishnamoorthy 1981), litter fall and nutrient return (Pandey and Singh 1981) and litter dynamics and microbial associations in *Acacia auriculiformis* plantations in Kerala (Sankaran et al. 1993) are available.

Gut loading time for different earthworm species was experimentally studied and estimated in five species of Indian earthworms found in pastures, crop fields and mixed woodlands. The gut loading time varied 2 h 15 min. to 10 h, depending on the size of the species and other factors. The gut filling time by an adult worm was found to vary from 2.4 times to 10.6 times day^{-1} in different species (*Octochaetona surrensis, Lampito mauritii, Drawida willsi, D. calebi*) using the same type culture material. Earthworms ingest about 15 kg of soil and litter material m^{-2} yr^{-1} and these amounts to about 7% of the total top soil and litter available on the site (Dash et al. 1984 and 1986). The relationship between the adult worm biomass and their gut contents was found to be positively significant. Such studies are needed to understand functional role of soil fauna in different land-uses in India.

Bioturbation in soil includes soil turnover by soil fauna, especially by earthworms. Satchell (1967) estimated that cast production in temperate sites would amount to 10-89 tons dry weight ha^{-1} yr^{-1}. Edwards and Lofty (1977) have estimated that worm cast production ranges from 2 to 247 tons ha^{-1} yr^{-1} depending on the ecological conditions. Studies done in Indian grasslands (Dash and Patra 1979) show cast production of 77 tons ha^{-1} yr^{-1} with highest rate of cast production in rainy season and lowest rate in summer. Bhadauria and Ramakrishnan (1991) estimated 20 tons, 35 tons, 40 tons cast production per year in a 5-year-old pine forest, a 35-year-old pine forest, and a sacred grove in North-East of India. The cast production was positively correlated to the earthworm biomass. Kollmanspergar (1956) working on mountain savanna in Cameroon estimated 207 tons of cast production ha^{-1} yr^{-1}. The high rate of soil turnover provides 15 cm thick stone free surface soil (Edwards and Lofty 1977). Estimation of cast production in different land uses would indicate the functional role of earthworms but such studies covering different land-uses and eco-regions in India are lacking.

Several studies in tropical soils (Nijhawan and Kanwar 1952) and in temperate soils (Guild 1952 and 1955, Low 1955, Petersen and Luxton 1982) have shown that earthworm casts contain more water soluble aggregates than the surrounding soils and a soil rich in aggregates remain well aerated and drained. Burrowing activity of earthworms increases soil aeration. Guild (1952 and 1955) found that soils with earthworms drain 4 to 10 times faster than soils without earthworms. Lavelle et al. (1996) have found that earthworms ingest on the average three times their body weight in the adult stage in tropical soils. In Indian pasture soil, Dash et al. (1984 and 1986) estimated that *Drawida willsi* and *D. Calebi* ingested soil 1-2 times of their body weight and *Lampito mauritii* and *Octochaetona surensis* 2 to 3 times their body weight daily. Earthworms transmit huge amount of soil, not less than 1000 tonnes in their gut annually (Dash 1987, Lavelle et al. 1996).

Earthworm casts are rich in nitrogeneous materials and partially digested organic matter. Satchell (1967) suggested that the soil particles in worm casts are stabilized by accumulation of polysaccharide gums produced by intestinal micro-organisms. Casts contain more nitrogen than the surrounding soil and casts provide good substrate for colonization and growth of micro-organisms. The increase in the amount of nitrogen in worm casts and soil rich in earthworms may be due to decay of dead worms and nephridial excretion and mucous secreted by the worms. Experimental studies indicate that a single adult dead *Lampito mauritii* can yield as much as 30 mg nitrogen and a population of 2 million earthworms ha^{-1} in tropical grassland could add 60 kg nitrogen ha^{-1} annum. Taking all the sources of nitrogen production by worms i.e. dead tissue, mucous production and nephridial excretion, an earthworm population might be contributing 180 kg of nitrogen ha^{-1} yr^{-1} (Satchell 1967, Dash 1999). The carbon: nitrogen ratio (C/N ratio) of freshly fallen litter is about 25:1 for elm, 28:1 for ash, 38:1 for lime, 42:1 for oak, 44:1 for birch, 91:1 for Scots pine trees (Wittichi 1953). Plants cannot assimilate mineral nitrogen unless the C/N ratio falls down to the order of 25 to 20: 1. Many studies show that the C/N ratio in soils with litter is brought down to less than 25: 1 by earthworm activity (Senapati and Dash 1982, Ndegwa and Thompson 2000).

Earthworm – Microflora – Microfauna Interaction

Soil biologists agree that microorganisms are the primary decomposing agents in natural decomposer systems. Dash et al. (1979 and 1985) isolated 16 species of micro-fungi from earthworm gut and 7 species of micro-fungi from freshly laid wormcasts. By carrying out laboratory experiments, they showed that earthworms grazed over and digested eight species of micro-fungi. However, the thick-walled spores surrounded by multilayer cleistothecium or perithecium of *Thievia vasinfecta* and wrinkled spore coat of *Neocosmospora vasinfecta* were not digested and laid in the worm cast. The worm casts are the loci for dissemination of some micro-fungi. Analysis of gut contents of five grassland earthworms showed that the worms digested micro-fungi, predated over non-parasitic nematodes and utilized plant litter (Dash et al.1979, 1980 and 1985). Similar conclusiongs are also drawn by Senapati (2002), Tiunov and Scheu (2000) and Dominguez et al. (2003). The ingestion of fungal material by adult population of five Indian epigeic and anecic species viz., *Drawida willsi, Drawida calebi, Lampito mauritii, Octochaetena surensis* and *Perionyx millardi* has been estimated as 176.27 mg, 489.59 mg, 1585.47 mg, 3794.62 mg and 26.16 mg m^{-2} yr^{-1}, respectively, and assimilated fungal biomass as 137.49, 264.38, 903.72, 1328.12 and 22.5 mg, respectively. Worms ingested 7% and assimilated 3% of the total fungal biomass available as standing crop.

In experimental studies, Dash et al. (1979) have found that earthworms feed mainly on non-parasitic nematodes and Dominguez et al. (2003) have found significant reduction in the numbers of bacterivore nematodes as sewage sludge passed in earthworm gut. Besides earthworms, mesofauna like enchytraeids and micro-arthropods, also play an important role in grazing of micro-organisms and as agents of dissemination of micro-organisms. Maximum number of microfungal species occurs in the fore gut gradually decreasing in the mid-gut and hind-gut with minimum numbers occurring in freshly laid cast (Dash et al. 1984 and 1986). The grazing activity over micro-organisms perhaps prevents ageing and enhances growth of microorganisms in soil (Dash et al. 1985). Analysis of the gut of earthworms and enchytraeids showed a wide variety of enzymes including cellulase (Mishra and Dash 1980). Haynes et al. (2003) showed the differences in physical, chemical and microbial properties of casts of endogeic species *Aporretodea caliginosa* and epigeic species *Lumbricus rubellus*. The microbial biomass, faunal biomass, their interaction and their relation to soil organic carbon, total nitrogen and total phosphorous are the important determinants of understanding of linkages between agricultural and natural ecosystem health mediated through soil fauna could be profitably used for sustainable landscape management.

Agro-Pesticides and their Effect on Earthworms

In modern intensive agricultural systems, organochlorine, organophosphates, carbamate and metal containing chemicals are used to control pests. Although earthworms are non-targeted animals, they are affected by these chemicals. Laboratory studies show that LC 50 values based on log dose vs probit mortality follow the order of *Lampito mauritii* > *Drawida willsi* >*Drawida calebi* >*Octochaetona surensis* (all epigeic or anecic species) for tolerance to monocrotophos; *Lampito mauritii* > *Drawida calebi* >*Octochaetona surensis* > *Drawida willsi* for tolerance to fenitrothion (Patnaik and Dash 1990). Worms become ureotelic and ammonotelic due to starvation with increasing trend of excretion when exposed to monocrotophos (Patnaik and Dash 1991). Cholinesterase activity of nerve and muscle tissues of *Lampito mauritii* and *Drawida calebi* were inhibited in both short term and continuous exposure to monocrotophos and fenitrothion. The recovery potential varied by species (Patnaik and Dash 1992 and 1993). Panda and Sahu (1999) studied effects of malathion on the growth and reproduction of *Drawida willsi* under laboratory conditions. The growth was inhibited in the first two weeks of application of the pesticide but worms recovered and normal growth and reproduction occurred after 105 days of application of malathion. Comparative toxicity data based on the effect of agrochemicals on Indian earthworms are not available from different areas enabling identification of suitable test species and confirmation of conclusions based on laboratory studies. *Lampito mauritii*, because of its common occurrence, will be suitable as the test species of choice for toxicity studies.

Earthworms immobilize and also excrete cadmium, cobalt, mercury, zinc, copper and lead in their tissues (Beyer and Cromartle 1978, Beyer et al. 1987, Marinussen et al.1997, Panda et al. 1999, Nahmani et al. 2003). Panda et al.(1999) worked on the accumulation and effect of zinc on the growth, reproduction and life cycle of *Drawida willsi* and found that earthworms were able to regulate their body content of zinc within a range of 116-125 mg kg^{-1} (dry weight). Reproduction and completion of life cycle was significantly affected negatively when Zn concentration in soil exceeded 200 mg kg^{-1}. Nahmani et al. (2003) worked in 11 sites including grasslands, cultivated soils and poplar plantations varying in the level of Zn, Cd, and Pb contamination and found that soil pollution reduced density as well as species richness of earthworms. *Aporrectodea caliginosa* and *Allolobophora chlorotica* appeared to be most sensitive to heavy metals. Although comprehensive data base on the effect of pesticides, and heavy metals on earthworms are yet to develop, there are evidences to show that earthworms tend to overcome the stress by increasing mucous secretion, reducing borrowing activity and increasing reproduction.

Crop Productivity and Wasteland Reclamation using Earthworms

Production and decomposition are two main life supporting activities and these processes can be understood well by understanding the soil food web and nutrient cycling. Earthworm species diversity and community structure are significantly influenced by land-use-land cover changes (Blanchart and Julka 1997, Bhadauria et al. 2000, Bhadauria and Ramakrishnan 2005, Maikhuri et al. 2005 and 2008, Kale and Dinesh 2005). Many invertebrates have been used as indicators to assess sustainable land-use (Paoletti 1999). Bhadauria and Ramakrishnan (2003 and 2005) reported that the epigeic species, *Bimastus parvus* and *Lennogaster yeicus* dominated the agroecosystems in central Himalaya probably due to higher input of farmyard manure. Earthworm distribution is dependent upon litter and organic matter input rates and chemical characteristics of these inputs which vary with land management practices. Surface earthworm cast production was monitored during maize cropping seasons and subsequent fallow phase by Norgrove et al. (2003). They observed that slashing of vegetation caused a severe decline in cast production irrespective of the fact whether the plots were cropped afterwards or not. Significantly lower cast production occurred when mulch was removed by burning than when it was removed by mechanical means. Under shifting agriculture in north-east India, earthworm population density declined significantly after slashing and burning (Bhadauria and Ramakrishnan, 1989). Understanding these processes is important for landscape management and waste land reclamation by using earthworms.

In a macrofauna research project funded by European Union, scientists conducted 16 experiments in Peru, Ivory Coast, India and Australia in six great groups of soils to study the effect of earthworm inoculation on plant production in field level and in green house studies (Brown et al. 1999). The overall average increase in shoot and grain biomass in plants due to earthworm inoculation was estimated as 56.3% $\pm$ 9.3% (SE) and 35.8% $\pm$ 8.9%, respectively. Highest biomass increase was observed in soils with sandy texture, poor in organic matter, and a moderately acid pH. Earthworm biomass of 30 g m^{-2} or more was required to raise grain yield by 40%. In Indian sites in south, the most promising earthworm species were *Drawida willsi* (epigeic-anecic) and *Pontoscolex corethrurus* (endogeic). It is important that locally adapted species are inoculated in the field and allowed to establish with proper management practices. Once establised, worms will provide long-lasting benefits. Senapati et al. (1999) suggested a graphical conceptual model for management alternative for earthworm technology. They reared *Pontoscolex corethrurus* in specific culture beds using low and high quality organic material and produced about 12,000 worms (1.6-2.8 kg live weight) m^{-2} yr^{-1}. They inoculated earthworms with proper management practices in tea gardens and found significant increase in tea production (Giri 2006).

Plant influences on native and exotic earthworms during secondary succession in old tropical pastures in Puerto Rico were studied by Leon and Zou (2004). Land-use changes drastically alter earthworm communities. Native species were often lost and few exotic species, such as *Pontoscolex corethrurus*, dominated following conversion of tropical forests to pastures. A shift in grass dominated vegetation to woody plants dominated vegetation followed a decrease in the density and biomass of the exotic species during secondary succession.

Many studies in European temperate climates (Whalen and Costa 2003, Muys et al. 2003, Scheu 2003) have shown that earthworms play key roles in nutrient cycling, modifying soil porosity and aggregate structure, controlling soil microbial communities, plant growth. Earthworms are often referred as "keystone organisms "in many terrestrial ecosystems as they are capable of affecting nutrient dynamics by altering soil physical, chemical and biological properties. Studies on their spatio-temporal variation in different land-uses will provide clues of their colonization pattern and possible utilization in wasteland reclamation.

Piearce et al. (2003) have used paper mill sludge and earthworms in land restoration. An experiment was conducted to investigate the effect of three earthworm species, epigeic - *Lumbricus rubellus*; anecic - *Lumbicus terrestris* and endogeic -*Aporrectodea calliginosa tuberculata* on bacterial community and nitrogen mineralization. It was found that the epigeic and anecic species enhanced mineralization of crop residue where as the endogeic had no effect (Postma-Blaauw et al. 2006). The interactions between different earthworms species affected the bacterial community and the net mineralization of soil organic matter suggesting the importance of interaction studies in identifying cost effective measures for prevention of nutrient losses and enhancement of soil fertility in agricultural systems.

Prasad et al. (1994) showed that conversion of natural forest led to reduction of soil organic C, total N, total P, micro-fungal biomass and total microbial biomass C, N and P over a 30-50 year period and ultimately it led to the loss of biological stability of the soil. Taking clues from European and American studies, inoculation of earthworms with proper feed material may help restoration of degraded soils. Identification of native epigeic, anecic and endogeic "keystone" earthworms in different land-uses in India will be helpful for wasteland reclamation. The introduction of exotic species will create problems and therefore, generally should be avoided.

VERMITECHNOLOGY

Earthworms (verms) are now utilized as vermifeed (protein source for fish and poultry), vermin-culture (production of worm cast, which are utilized as vermin-manure and as water holding substrate for growth of edible mushrooms) and field inoculants for increasing plant productivity, and as biological tools of converting organic waste into manure through vermi-composting. The technology of utilization of earthworms is called vermitechnology (Figure 1).

Vermiprotein

Earthworm tissue contains more than 50% proteins on dry weight basis (Dash et al, 1977).Essential amino acids are available in their body tissue. In an experiment, earthworm dry tissue was fed to Japanese quails and chicks and evaluated as a substitute for fish meal. Two diets, each with 23% protein, were used: (i) a control ration with 9.4% fish meal and (ii) test ration with 9.4% gut cleaned earthworm tissue meal. The mean weight gains for broilers was 1.12 kg and 1.17 kg, feed consumption over 46 days 2.528 kg and 2.524 kg, feed conversion ratio 2.263 and 2.154 and mean growth rate (kg day^{-1}) 0.024 and 0.025, respectively, for fish meal and earthworm meal ration treatments (Das and Dash 1989 and 1990).
Cultivation of edible mushroom (*Pleurotus sajor caju*) using wheat supplement in a paddy straw substrate was tested and compared with earthworm casts replacing wheat supplement. Cellulose and water were more efficiently used by the mushrooms when worm casts were used and it resulted in increased mushroom yield (Dash and Das 1989).

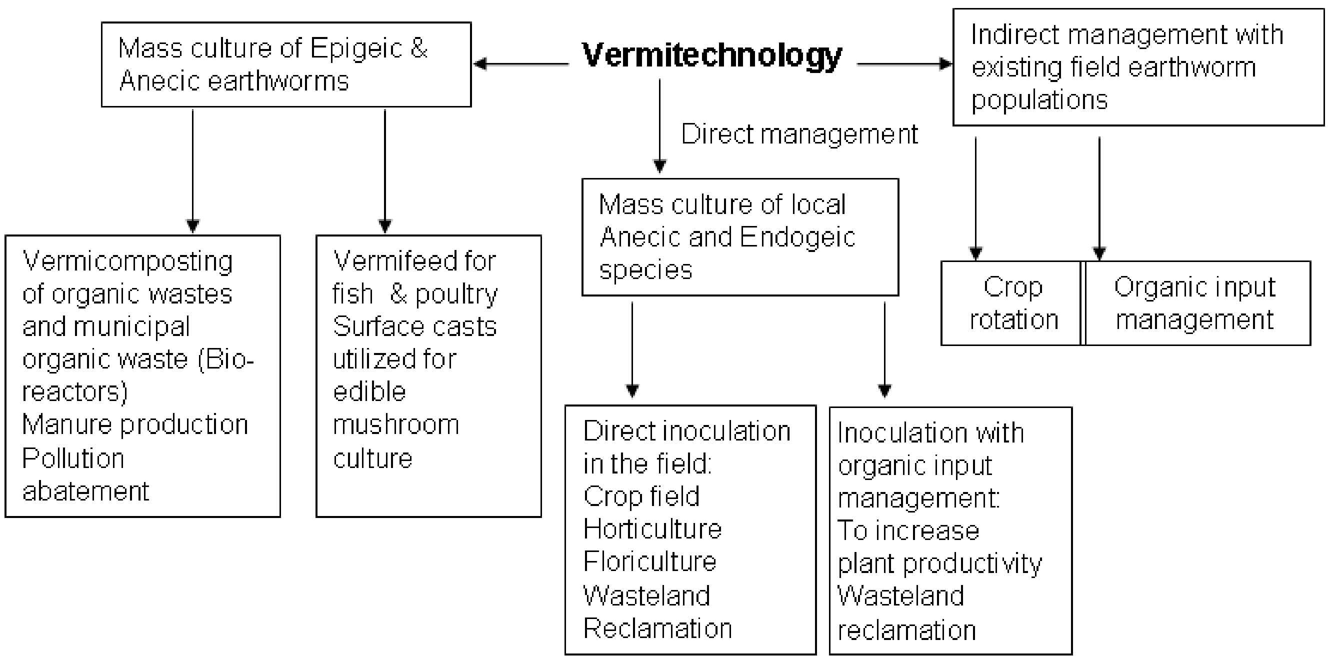

Figure 1. Utilization of earthworms in various applications of vermitechnology

Vermicomposting

The science of vermicomposting took shape during mid-20th century when the first vermicomposting plant was set up in Holland's Landing, Ontario, Canada (Appelhof 1980 and 1981). Subsequently the technology has become very popular all over the world and has under gone several modifications (Hartenstein et al. 1979, Collier and Livingstone 1981, Dash and Senapati 1985 and 1986, Singh 1997, Ndegwa and Thompson 2000, Gajalakshmi et al. 2001, Frederickson and Howell 2002, Arancon et al. 2002 and 2003a,b, Chaudhuri et al. 2003, Pizi and Novakova 2003, Tripathi and Bhardwaj 2004, Loh et al. 2005, Garg et al. 2006, Sen and Chandra 2007, Pramanik et al. 2007, Suthar 2007, Clarke et al. 2007, Tognetti et al. 2007, Padmavathi-amma et al. 2008).

Eudrilus eugeniae, Eisenia foetida and *Perionyx excavatus* are most commonly used for vermicomposting. The changes in C/N ratio, C/P ratio, concentration of N, P and K, Phosphatase activity in worm casts, microbial interactions, and some other parameters have been taken as criteria for judging the efficiency of earthworms in the vermicomposting process. The reproductive fitness of the worm, growth and mortality factors based on the feeding pattern have also received attention of research workers (Reinecke and Viljoen 1990). In recent times importance is given to local and endemic species due to outbreak of foot-and-mouth disease and fungal pathogens in Europe arising from earthworm import (Hendrix and Bohlen 2002).

The exotic African species, *Eudrilus eugeniae* is being used in many centres in India. There is serious threat of this species invading the natural ecosystems and thereby a possibility of loss of endemic species. Another exotic species *Eisenia foetida* is also used in India. This species was introduced before India's independence and this species has been colonized in many natural ecosystems. Bhadauria and Ramakrishnan (2005) have found many exotic species in North-east and Central Himalaya. The ecological implications have not been fully assessed. However, some research work for vermicomposting in India has given importance to local species. The data available indicate that a number of Indian species may be suitable for vermicomposting (Dash and Senapati 1985 and 1986, Dash 1994 and 1999, Singh1997, Gajalakshmi et al. 2001). Research on screening of potential of Indian earthworm species for vermitechnology purpose should be considered a thrust area for research funding.

Table 3. Vermiculture [illegible]

Table 3 gives comparative account of the vermicultural characteristics of some Indian earthworms including, *Perionyx excavatus, Eisenia foetida* (=*fetida*) and the exotic, *Eudrilus eugeniae*. There is need of research to standardize the bioreactor conditions, quality of organic waste-substrate and quality of vermicompost and a protocol for application of vermicompost. Indian earthworm species like *Perionyx excavatus*, *Lampito mauritii, Drawida willsi, Drawida bolui* and *Perionyx sansibaricus*, are considered suitable for vermicompsting of organic wastes.

CONCLUSION:

Earthworms dominate soil faunal biomass in many Indian ecosystems. India has rich earthworm biodiversity, having about 10% of earthworm resources of the world. Their functional role in many land uses, although appear to be very important for land use management but is yet to be fully understood. Some of the native species have the potentiality for use in vermitechnology, for increasing crop productivity and waste land reclamation. Research efforts are to be supported for utilizing them to increase soil fertility and for sustainable development.

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Table 2. Density, biomass and annual production of earthworms (m^{-2}) in different Indian sites

Land use/ ecosystems	Diversity	Density	Average / Range Biomass (wet wt, g)	Average / Range Production (g)	Trends	Ref.
Pastures, Berhampur, Orissa	Two Species (*Lampito mauritii, Ocnerodrilus occidentalis*)	18-88	6-61	126-140	Peak density after monsoon in early winter	1
Pasture,Bangalore, Karnataka		25-936				2
Orchad, Bangalore, Karnataka		38.2-420.5				2
Barren land , Bangalore, Karnataka		138.6-398.1				2
Arable land, Bangalore, Karnataka		51.9-274.4				2
Pine woodland, Shillong, Meghalaya		8.8-52	4.4-9.4			3
Grasslands, Sambalpur, Orissa	Five species (*Drawida calebi, D. willsi, Lampito mauritii, Octochaetona surensis, Ocnerodrilus occidentalis*)	-	9.78-77.68	134	Peak density immediately after monsoon in early winter	4
Mixed deciduous forest, Sambalpur, Orissa	Four Species (*Lampito mauritii, Drawida calebi, Rameila bishambari, Pellogaster bengalensis*)	24-131	7-28.5	78	Peak density in October	5
Mixed woodland, Solan, Himachal Pradesh	-	30.4-118.4				6
Humid tropical deciduous forest, Andhra Pradesh	Five species (*Amynthas alexandri, A. diffringens, Metaphire posthuma, M. houlleti, Dichogaster* sp.)	315 (28-281 in different microsites)			Two peaks during and end of the rainy season	7
Shifting agriculture in NE India (Nangpoh)	Three species (*Megascolides antrophytes, Drawida assamensis, Nelloscolex strigosus*)	68	-	-	Immediately after rainy season	8
Shifting agriculture in NE India (Shillong)	Five species (*Amynthas . diffringens, Drawida assamensis, Eutyphoeus festivus, Nelloscolex strigosus, Tonoscolex horaii*)	4-47 in cropping phase, 50 in fallow phase	-	-	Peak density during rainy season except *Amynthas diffringens* which peaks in winter	9
Upland irrigated rice field, Sambalpur,	Five species (*Drawida calebi, D. willsi, Lampito mauritii, Ocnerodrilus occidentalis, Octochaetona surensis*)	1399	-	-	Peak density in monsoon (August-September)	10

Table 2. (Continued)

Land use/ ecosystems	Diversity	Density	Average / Range Biomass (wet wt, g)	Production (g)	Trends	Ref.
Pasture, Kumaon Himalaya	Three species (*Amynthas diffringens, Amynthas alexandri, Eisenia fetida*)	138.8	25.2	-	Peak density at the end of rainy season (Oct.-Dec.)	11
Cultivated soil, Kumaon Himalayas	One species, *Amynthas alexandri*	58.4	-	-	Peak density during rainy season	12
Sites in Varanasi, Uttar Pradesh	Eleven species (*Dichogaster bolaui, Eutyphoeus incommodus, E. nicolsoni,E. waltoni, Octochaetona surensis*, *Ramiella bishambari, Amynthas morrisi*, *Lampito mauritii, Metaphire posthuma, Drawida calebi, Glyphidrilus* sp.)	-	-	-	Grass land, cultivated soil, non-cultivated soil, garden soil, sewage soil	13
Village landscape, Central Himalaya (mid elevation)	Eight species (*Bimostus parvus, Octolasion tyrtaeum, Octochaetona beatrix, Amynthas corticis, Eutyophoeus festivus, E. nanianus, E. waltonii, Drawida* sp.)	Climax forest 526, Mixed forest 309, Five yr-old pine 287, 40 yr-old pine 940, Grassland 353	-	-	Peak density during rainy season	14
Cropland,Pasture,Garbage sites, Ranchi, Jharkhand	Twelve species (*Lampito mauritii, Drawida calebi, D.bolaui, D. affinis, Metaphire planate, M.posthuma, Perionyx sansibaricus, Ocnerodrilus occidentalis, Lennogaster bengalensis, Glyphidrilus tuberosus, Pontoscolex corethrurus. Pellogaster bengalensis*).	Cropland 2585 (75-7600)	11.32 (0.57-30.01)		Peak density in August (rainy season) Cropland only 1 species *Ocnerodrilus occidentalis*	15 16
Village landscape, Garhwal Himalaya (mid elevation)	Seven species (*Amynthas corticis,Drawida nepalensis, Allbophora parva, Eutyphoeus pharpingianus, Octochaetona beatrix, Perionyx* sp., *Lennogaster pusillus*)	Forests 108-247, Agro-ecosystema 89-235	-	-	Higher abundance but lower diversity in pine forest than in oak forest	16

Table 2. (Continued)

Land use/ ecosystems	Diversity	Density	Average / Range Biomass (wet wt, g)	Average / Range Production (g)	Trends	Ref.
Nandadevi Biosphere Reserve, Central Himalaya	Eight species (*Lennogaster pusillus,Metaphire houlleti, M. anomala, Ocnerodrilus occidentalis, Dendrodrilus rubidus, Aporrectodea calliginosa, Amynthus corticis, Drawida nepalensis*)	**Lower elevation:** home garden 100, pine forest 5-10, oak forest 5, irrigated agriculture 5, rainfed agriculture 5-25 **Higher elevation:** home garden 10-150, alpine pasture 5-25, alpine forest 10-15	home garden 3, pine forest 2, oak forest 2, rainfed agriculture 1, home garden 35, alpine pasture 7, alpine forest 10		Peak density at the end of rainy season- winter	17
Nilgiri Biosphere Reserve, Kerala	Fourteen Species (*Dichogaster affinis, Drawida modesta, D. barwelli impertusa, D.ghatensis, D. grandis, Glyphidrilus annandalei, Haplochetalla sp., Lampito mauritii, Megascolex insignis, M. triangularis, Octochaetona beatrix, Parryodrilus lavellei, Plutellus variabilis, Pontoscolex corethrurus*)	Moist deciduous forest 215 Degraded forest 2, Teak forest + plantation 84, Annual crops 24, Home garden 46 Polyculture farm 60, Arecanut with annuals 27 Arecanut with perennials 55 Coconut with perennials 294 Plantations: Arecanut 157, Coconut 36, Rubber 50, Cashew 150, Teak 121				18

1. Dash and Patra 1977; 2. Kale and Krishnamoorthy 1978; 3. Reddy and Alfred 1978; 4. Dash and Senapati 1981; 5. Mishra and Dash 1984; 6. Julka and Mukherjee 1984; 7. Reddy 1987, 8. Mishra and Ramakrishnan 1988, 9. Bhadauria and Ramakrishnan 1989, 10. Senapati 1992, 11. Kaushal and Bisht 1994; 12. Kaushal et al. 1995; 13. Singh 1997, 14. Bhadauria and Ramakrishnan 2000, 15. Sinha et al. 2002; 16. Sinha et al. 2003; Maikhuri et al. 2008; 18. Chandrashekara et al. 2008.

Table 3. Vermiculture characteristics of some Indian earthworms suitable for vermicomposting

Species	Soil temperature for maximum growth	Age for cocoon production (weeks)	Upper limit of soil temperature tolerance (°C)	Vermi-stablization time (weeks)	No of young / cocoon	Incubation period (weeks)	Average size live weight (g)
Perionyx excavatus	25-30	15	30	4-5	1-2	4	1
Lampito mauritii	18-30	8	30	3	1	4	1
Octochaetona surensis	20-25	15	27	8-10	1	4	1
Drawida willsi	20-25	8	30	3-4	2-3	2	0.5
Dichogaster bolaui	25-30	7	33	3	1-2	1	0.1
*Eudrillus eugeinae***	20-25	8	30	3-4	2-3	4	1
Eisenia foetida	18-25	7	25	6-8	2-4	3-4	0.5

** African worm (exotic)