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Review Article

Role of Earthworms in Soil Fertility Maintenance through the Production of Biogenic Structures

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The soil biota benefits soil productivity and contributes to the sustainable function of all ecosystems. The cycling of nutrients is a critical function that is essential to life on earth. Earthworms (EWs) are a major component of soil fauna communities in most ecosystems and comprise a large proportion of macrofauna biomass. Their activity is beneficial because it can enhance soil nutrient cycling through the rapid incorporation of detritus into mineral soils. In addition to this mixing effect, mucus production associated with water excretion in earthworm guts also enhances the activity of other beneficial soil microorganisms. This is followed by the production of organic matter. So, in the short term, a more significant effect is the concentration of large quantities of nutrients (N, P, K, and Ca) that are easily assimilable by plants in fresh cast depositions. In addition, earthworms seem to accelerate the mineralization as well as the turnover of soil organic matter. Earthworms are known also to increase nitrogen mineralization, through direct and indirect effects on the microbial community. The increased transfer of organic C and N into soil aggregates indicates the potential for earthworms to facilitate soil organic matter stabilization and accumulation in agricultural systems, and that their influence depends greatly on differences in land management practices. This paper summarises information on published data on the described subjects.

1. Introduction

Protection of the soil habitat is the first step towards sustainable management of its biological properties that determine long-term quality and productivity. It is generally accepted that soil biota benefits soil productivity but very little is known about the organisms that live in the soil and the functioning of the soil ecosystem. The role of earthworms (EWs) in soil fertility is known since 1881, when Darwin (1809–1882) published his last scientific book entitled "The formation of vegetable mould through the action of worms with observations on their habits." Since then, several studies have been undertaken to highlight the soil organisms contribution to the sustainable function of all ecosystems [1]. Soil macrofauna, such as EWs, modify the soil and litter environment indirectly by the accumulation of their biogenic structures (casts, pellets, galleries, etc.) (Table 1). The cycling of nutrients is a critical ecosystem function that is essential to life on earth. Studies in the recent years have shown increasing interest in the development of productive farming systems with a high efficiency of internal resource use and thus lower input requirement and cost [2, 3]. At present, there is increasing evidence that soil macroinvertebrates play a key role in SOM transformations and nutrient dynamics at different spatial and temporal scales through perturbation and the production of biogenic structures for the improvement of soil fertility and land productivity [4, 5]. EWs are a major component of soil fauna communities in most natural ecosystems of the humid tropics and comprise a large proportion of macrofauna biomass [6]. In cultivated tropical soils, where organic matter is frequently related to fertility and productivity, the communities of invertebrates—especially EWs—could play an important role in (SOM) dynamics by the regulation of the mineralization and humification processes [7–9].

Table 1: Some properties of casts of *Pheretima alaxandri* and their underlying soils with and without litter cover [10].

	Soil without litter		Soil with litter	
	Surface soil	Worm cast	Surface soil	Worm cast
pH	5.65	7.70	6.25	6.30
Organic Carbon (%)	1.52	1.70	2.66	3.36
Available P_2O_5 (mg 100 g^{-1})	0.15	0.24	0.19	0.22
Available K_2O (mg 100 g^{-1})	3.31	4.78	5.98	7.36

Table 2: Effect of land conversion and management practices on changes in functional catagories of earthworms in the Indo-Gangetic plains, (±SE, $n = 10$).

Sites	Density (*Anecic*) (Individuals m^{-2} $year^{-1}$)	Biomass (*Anecic*) (gm^{-2} $year^{-1}$)	Density (*Endogeics*) (Individuals m^{-2} $year^{-1}$)	Biomass (*Endogeics*) (gm^{-2} $year^{-1}$)
Primary forest	$_{1}41$ $(\pm 3.2)^{a}$	$_{1}23$ $(\pm 11.6)^{a}$	$_{2}127$ $(\pm 13.8)^{a}$	$_{2}255.8$ $(\pm 20.6)^{a}$
Productive agroecosystem	$_{1}141$ $(\pm 11.6)^{b}$	$_{1}323$ $(\pm 23.5)^{b}$	$_{2}75$ $(\pm 6.3)^{b}$	$_{2}157.5$ $(\pm 13.3)^{b}$
Low productive agroecosystem	$_{1}106$ $(\pm 7.9)^{c}$	$_{1}318$ $(\pm 27.8)^{b}$	$_{2}45$ $(\pm 3.2)^{c}$	$_{2}94.5$ $(\pm 6.8)^{c}$
Agriculture fallow	$_{1}64$ $(\pm 3.8)^{d}$	$_{1}42$ $(\pm 2.9)^{c}$	$_{2}274$ $(\pm 14.6)^{d}$	$_{2}518.7$ $(\pm 42.6)^{d}$
Sodic ecosystems	0	0	0	0
5-year-old reclaimed agroecosystem	0	0	143 $(\pm 12.7)^{e}$	114.4 $(\pm 5.8)^{c}$
10-year-old reclaimed agroecosystem	0	0	282 $(\pm 24.7)^{d}$	160.6 $(\pm 15.3)^{b}$
Acacia plantation in reclaimed soils	$_{1}44(\pm 5.3)^{a}$	$_{1}132$ $(\pm 5.9)^{a}$	$_{2}133$ $(\pm 9.6)^{a}$	$_{2}279.3(\pm 21.5)^{e}$

Values followed by the different superscript letters are significantly different in different sampling sites. Values followed by different subscript numbers are significantly different in same sampling sites [11].

1.1. Functional Significance of Earthworms. The effects of EWs on soil biological processes and fertility level differ in ecological categories [12]. Anecic species build permanent burrows into the deep mineral layers of the soil; they drag organic matter from the soil surface into their burrows for food. Endogeic species live exclusively and build extensive nonpermanent burrows in the upper mineral layer of soil, mainly ingested mineral soil matter, and are known as "ecological engineers," or "ecosystem engineers." They produce physical structures through which they can modify the availability or accessibility of a resource for other organisms [13]. Epigeic species live on the soil surface, form no permanent burrows, and mainly ingest litter and humus, as well as on decaying organic matter, and do not mix organic and inorganic matter [14]. In the majority of habitats and ecosystems (Table 2), it is usually a combination of these ecological categories which together or individually are responsible for maintaining the fertility of soils [15–17].

1.2. Role of Earthworms in Nutrient Availability to Soil. EWs influence the supply of nutrients through their tissues but largely through their burrowing activities; they produce aggregates and pores (i.e., biostructures) in the soil and/or on the soil surface, thus affecting its physical properties, nutrient cycling, and plant growth [19, 20]. The biogenic structures constitute assemblages of organo-mineral aggregates. Their stability and the concentration of organic matter impact soil physical properties and SOM dynamics. Besides they affect some important soil ecological processes within their "functional domain" [21, 22] where they concentrate nutrients and resources that are further exploited by soil microorganism communities [23, 24]. The effect of EWs on the dynamics of organic matter varies depending on the time and space scales considered [25]. The activity of endogeic EWs in the humid tropical environment accelerates initial SOM turnover through indirect effects on soil C as determinants of microbial activity. Due to selective foraging of organic particles, gut contents are often enriched in organic matter, nutrients, and water compared with bulk soil and can foster high levels of microbial activity [26, 27]. They have been reported to enhance mineralization by first fragmenting SOM and then mixing it together with mineral particles and microorganisms, and thereby creating new surfaces of contact between SOM and microorganisms [28]. In the short term, a more significant effect is the concentration of large quantities of nutrients (N, P, K, and Ca) that are easily assimilable by plants in fresh cast depositions [18]. Most of these nutrients are derived from earthworm urine and mucus [29]. In highly leached soils of humid tropics, earthworm activity is beneficial because of rapid incorporation of the detritus into the soils [30]. In addition to this mixing effect, mucus production associated with water excretion in the earthworm gut is known to enhance the activity of microorganisms [31]. This is followed by the production of organic matter. So fresh casts show high nutrient contents

Table 3: Variation in nutrient concentration of earthworm casts and noningested soils during cropping under shifting agriculture in North East India (±SE, $n = 5$) [18].

	5-year-cycle		15-year-cycle	
	Soil	Worm cast	Soil	Worm cast
Organic Carbon (%)	2 (±0.1)	*2.5 (±.13)	3.2 (±.17)	**4.5 (±.23)
Total Nitrogen (%)	0.22 (±0.01)	*0.29 (±.17)	0.4 (±.03)	*0.6 (±.04)
Available Phosphorus (mg/100 g)	0.9 (±0.03)	*1.4 (±.09)	2.0 (±.06)	**2.8 (±.15)
Potassium (meq/100 g)	0.5 (±0.02)	0.54 (±.04)	1.2 (±.05)	*2.0 (±.09)
Calcium (meq/100 g)	0.9 (±0.01)	*1.2 (±.08)	1.5 (±.04)	**2.5 (±.13)
Magnesium (meq/100 g)	1.2 (±0.05)	*1.8 (±.09)	3.1 (±.17)	*4.0 (±.34)

* $P < .05$, ** $P < .01$.

Table 4: Variation in nutrient concentration of earthworm casts and non ingested soils in abandoned agricultural fallows in North East India (±SE, $n = 5$) [18].

	5-years-old fallow		10-years-old fallow		15-years-old fallow	
	Soil	Worm cast	Soil	Worm cast	Soil	Worm cast
Organic Carbon (%)	1.2 (±.07)	*3.5 (±.09)	1.9 (±.09)	**4 (±.03)	2.2 (±.13)	**5.2 (±.04)
Total Nitrogen (%)	0.22 (±.01)	*0.55 (±.02)	0.25 (±.03)	**0.59 (±.02)	0.21 (±.04)	*0.62 (±.05)
Available Phosphorus (mg/100 g)	0.38 (±.02)	*1.1 (±.05)	0.5 (±.01)	**1.8 (±.07)	0.54 (±.01)	*1.7 (±.05)
Potassium (meq/100g)	0.24 (±.01)	*0.61 (±.32)	0.4 (±.03)	*1.0 (±.05)	0.42 (±.01)	*0.90 (±.02)
Calcium (meq/100 g)	0.19 (±.03)	*0.60 (±.03)	0.22 (±.02)	**0.75 (±.01)	0.22 (±.01)	*0.85 (±.02)
Magnesium (meq/100 g)	0.22 (±.01)	*0.50 (±.01)	0.2 5 (±.04)	*0.60 (±.01)	0.32 (±.01)	*0.70 (±.01)

* $P < .05$, ** $P < .01$.

(Table 3). The chemical characteristics of casts differ from those of noningested soil [32] and are rich in plant available nutrients. Upon cast deposition, microbial products, in addition to earthworm mucilages, bind soil particles and contribute to the formation of highly stable aggregates [33, 34]. Although EWs may speed up the initial breakdown of organic residues [35, 36], several studies have indicated that they may also stabilize SOM through its incorporation and protection in their casts [37–40]. Over longer periods of time, this enhanced microbial activity decreases when the casts dry, and aggregation is then reported to physically protect SOM against mineralization. Thus C mineralization rate decreases and mineralization of SOM from casts may be blocked for several months [37, 41]. It might become accessible again for the microflora once these are degraded into small fragments [42–44]. In addition EWs seem to accelerate the mineralization as well as the turnover of SOM [45]. Furthermore, studies have also indicated that organic matter in the casts, once stabilized, can maintain this stabilization for many years [46, 47]. Nevertheless, chemical mechanisms may also contribute to the stabilization since evidence shows that the casts are held together by strong interactions between mineral soil particles and SOM that is enriched in bacterial polysaccharides and fungal hyphae [48, 49]. Earthworm casts are enriched in organic C and N, exceeding the C and N contents of the non ingested soil by a factor of 1.5, and 1.3, respectively (Table 4). This enrichment appears in all particle-size fractions, not restricted to certain organic compound dynamics of a cultivated soil [50]. These results clearly indicate the direct involvement of EWs in providing protection of soil C in microaggregates within large macroaggregates leading to a possible long-term stabilization of soil C [51] (Table 5). It has also been reported that EWs increase the incorporation of cover crop-derived C into macroaggregates, and more important, into microaggregates formed within macroaggregates. The increased transfer of organic C and N into soil aggregates indicates the potential for EWs to facilitate SOM stabilization and accumulation in agricultural systems [52].

EWs are known also to increase nitrogen mineralization, through direct and indirect effects on the microbial community (Table 6). Our studies on the role of EWs in the nitrogen cycling during the cropping phase of shifting agriculture in North East India showed (Table 7) that the total soil nitrogen made available for plants through the activity of EWs was higher than the total input of nitrogen to the soil through the addition of slashed vegetation, inorganic and organic manure, recycled crop residues, and weeds [54]. An important role of EWs is the dramatic increase in soil pH as observed through our studies in shifting agroecosystem in North East India, in a sedentary terrace agroecosystem in central Himalayas, and in intensive agroecosystem in Indo-Gangetic plains. This increases microbial activity and N fixation in the soil, so that nitrogen in the worm cast may be due at least in part to this rather than to concentration by gain worms. Nitrogen mineralization by microflora is also quite intense in the earthworm gut and continues for several hours in fresh casts [55, 56], respectively, by incorporating organic matter into the soil and or by grazing the bacterial community. EWs have been found to either enhance or decrease bacterial biomass [57–59], and to stimulate bacterial activity [60, 61]. The influence of EWs on N cycling,

Table 5: C and N contents and C : N ratio in particle-size organic fractions in control soil and cast of *Pontoscolex corethrurus* (±SE) [53].

Particle size (μm)	Laguna Verde		La Mancha	
C(mg g^{-1} soil)	Soil	Casts	Soil	Casts
2000–250	32.8 ± 5.1	51.2 ± 2.8	13.8 ± 8.4	7.1 ± 2.4
100–50	48.8 ± 4.7	54.1 ± 1.3	1.6 ± 0.6	1.5 ± 0.9
50–20	48.5 ± 7.6	63.4 ± 4.8	21.9 ± 9.6	17.1 ± 2.3
20–2	50 ± 4.2	22.4± 13.7	15.2 ± 6.7	29.5 ± 5.1
N(mg g^{-1} soil)				
2000–250	4.72 ± 1.2	4.35 ± 0.10		
100–50	4.35 ± 0.2	5.24 ± 0.60	0.21 ± 0.01	2.2 ± 0.22
50–20	4.06 ± 0.4	5.04 ± 0.04	1.91 ± 0.20	2.4 ± 0.20
20–2	4.20	4.76 ± 0.40	2.46 ± 1.02	2.8 ± 0.9
C : N ratio				
2000–250	8.8	11.8		
100–50	10.8	10.3	7.6	6.8
50–20	12.0	12.6	11.5	7.1
20–2	11.9	4.7	6.2	10.5

Table 6: Total and mineral nitrogen content in soil and fresh casts from earthworms incubated in different soil types (Barois et al., 1992 [53]).

Soil type	Layer (cm)	Earthworm species	Soil		Worm cast	
			N total (%)	Mineral N (μg g^{-1})	N total (%)	Mineral N (μg g^{-1})
Andisol, Martinique	0–10	Pontoscolex corethrurus	15.5	516.8	15.7	1095.1
Andisol, Mexico	0–10	Pontoscolex corethrurus	4.8	55.4	4.9	625.1
Luvic, Cuba	0–10	Onychochaeta elegans	2.6	55.4	2.4	212.5
Ultisol, Yurimaguas	0–10	Pontoscolex corethrurus	1.37	30	1.47	150.5
Vertisol, Lamto	0–10	Protozapotecia australis	3	52.1	4	560.9

Table 7: Nitrogen input/output budget during the cropping phase under 5- and 15-year Jhum cycle, (±SE, $n = 5$) [54].

	Nitrogen balance (kg ha^{-1} yr^{-1}) in different shifting agriculture cycles	
	5-years	15-years
INPUT		
Slash	27.60 (±1.30)	51.4 (±3.6)
Organic manure	14.0 (±1.1)	—
Inorganic fertilizer	0.80 (±.04)	—
Crop biomass	0.42 (±.05)	0.9 (±.01)
Weed biomass	2.85 (±1.1)	0.7 (±.03)
Precipitation	4.20 (±.28)	4.2 (±.26)
Input subtotal	**49.90**	**57.2**
Worm casts	27.0 (±1.3)	65.6 (±4.8)
Worm tissues	9.5 (±.13)	12.1 (±1.4)
Mucus production	75.9 (±3.2)	95.3 (±4.5)
Input total	****112.4**	****173.0**
OUTPUT		
Fire	277.6 (±23.2)	657.9 (±23.9)
Sediment	158.0 (±10.2)	116.0 (±4.5)
Percolation	1.0 (±.04)	1.2 (±.08)
Runoff	7.3 (±0.3)	14.0 (±1.3)
Weed removal	14.25 (±3.86)	3.33 (±.26)
Crop removal	15.24 (±1.28)	43.52 (±3.20)
Output total	**474.39**	**835.96**
Input-Output difference	**312.12**	**605.75**

however, appears also to be largely determined by cropping system type and the fertilizer applied (mineral versus organic). Various experimental studies suggest that EWs have potentially negative consequences on fertilizer-N retention studies [62]. The earthworm species and species interactions present in the system also effect nitrogen mineralization and crop production [63]. This may result in enhanced nitrogen immobilization or mineralization depending on species characteristics and substrate quality. The review thus highlights the important effects that EWs have on C and N cycling processes in agroecosystems and that their influence depends greatly on differences in management practices [64]. Further the EWs can also increase nutrient availability in systems with reduced human influence and low nutrient status, that is, no tillage, reduced mineral fertilizer use, and low organic matter content [65–67]. The role of EWs in improving soil fertility is ancient knowledge which is now better explained by scientific results emerging from different studies. This is an important field of study where the research is directly linked to the social welfare [68]. Every involved step requires appropriate protocols and reproducible results. This is a feedback mechanism where the technology adopted in the fields is further improved in the laboratories based on the feedback received from the technology adopters so as to provide more convincing information to technology adopters.

2. Future Research Needs

Most of the studies conducted to assess the role of earthworm casting in nutrient cycling and soil structure are related to surface casting species, and only a few have dealt with casts deposited under field conditions [5, 18, 54]. To reach a better understanding of the ecological impact of in-soil casts, the assessment of nutrient dynamics in earthworm burrows and on the effect of in-soil casts on plant growth would be of immense help. For below-ground casting earthworm species, the ecological impact of their below-ground casts is likely to be as important as their surface casts in relation with nutrient availability, especially for biological management of degraded and disturbed ecosystems. Therefore more research is needed to be done in this area to complete our knowledge of the role of EWs in nutrient dynamics so as to evolve strategies for better soil management techniques.

3. Conclusions

Considering the potential contribution of EWs to soil fertility management, there is the need to consider them in agroecosystem management decisions. The EWs can specifically affect soil fertility that may be of great importance to increase sustainable land use in naturally degraded ecosystems as well as agroecosystems. Proper earthworm management may sustain crop yields whilst fertilizer inputs could be reduced. Since farming can involve many soil disturbing activities, the understanding of the biology and ecology of EWs will help devise management strategies that may impact soil biota and crop performance.

Abbreviations

EW: earthworm
SOM: soil organic matter.

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