Role of earthworm in improving soil structure and functioning

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Earthworms commonly occur within the soil. They alter physico-chemical and biological regimes of the soil through their activities, such as burrowing, casting, feeding and propagating, and therefore are known as 'ecosystem engineers'. Through their activities, they provide a number of ecosystem services which are ecologically and socio-economically important. This paper reviews the role of earthworms in improving soil structural and functional properties, which serves as key determinants of soil ecosystem services and economic benefits for the farmers. A methodology of economic evaluation of the agro-ecosystem services provided by earthworms has been demonstrated. Further, the information gaps and future research have been discussed for ensuring sustainable agro-ecosystems management.

Keywords: Earthworm, economic evaluation, soil ecosystem services, soil aggregation, sustainable agriculture.

ECOSYSTEM services include an array of direct and indirect benefits provided by natural ecosystems for the well-being of human societies and represent part of the economic value of the planet[1]. Soil-forming processes account for more than one third of the average value of the total ecosystem services (33 Trillion US $) (Costanza *et al* 1997). In general, biodiversity is the basis of these ecosystem services at every aspect[2]. Earthworms play an important role in the soil-forming process and therefore considered as 'keystone species'[2] and described as 'ecosystem engineers', a vastly popular term proposed only in 1994 (refs 5 and 6). They are also called 'ecosystem services managers' as they act as a potential partner of human beings[7].

Earthworms have been categorized into three principal ecological groups depending upon the ecosystem processes and the services they provide (Figure 1). For example, most common epigeic species produce soil roughness and macro-pores by inhabiting litter and producing casts at the soil surface. Anecic species extend down the soil layer as they live in vertical burrows. The third category is the endogeic species, which make horizontal or randomly oriented burrows through all the layers of the upper soil and feed on decayed organic matter[8].

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Earthworms act as a catalyst in enhancing the crop yield (Table 1), but their effect depends on the amount of crop residue, earthworm density and rate of fertilization[9]. However, they always provide materials and energy outputs which have monetary values. They also carry out a range of functions by supporting life through regulating bio-geochemical cycles and other biosphere processes such as, decomposition, climate, pollution remediation and biodiversity interaction. Moreover, earthworm's life processes lead to several other services which are necessary for the functioning and self-sustainability of agro-ecosystems. These services include primary production, nutrient cycling, soil structure development and soil hydraulic functions, to name a few. Earthworm is also an important component of education to students to demonstrate the decomposition and recycling of organic matter. The services of earthworms are still not recognized and there is a lack of awareness of its ecological and economic benefits.

The objectives of this review are (i) to discuss the role of earthworms in transforming soils and (ii) to evaluate the potential role of earthworms in the agro-ecosystem services.

Earthworm services to the soil and agro-ecosystem

Soil structural development

Development of soil structure from micro- to macro-scale is a function of interacting physical forces of soil water content, actions of large biota like plant roots and earthworms, presence of organic matter in the soil and tillage[10]. The most prominent effect of the earthworm is on the reorganization of soil structure while moving through the soil, feeding on the soil[11] and release of material due to their low assimilation efficiency.

Earthworms can either make the soil compact or loose, depending on the species and its interaction with the soil. Anecic and endogeic species are responsible for a majority of physical improvements in soil structure through cast production in vertical and horizontal burrows. Cast production modifies soil bulk density through incorporation of organic matter into the soil. For example, an

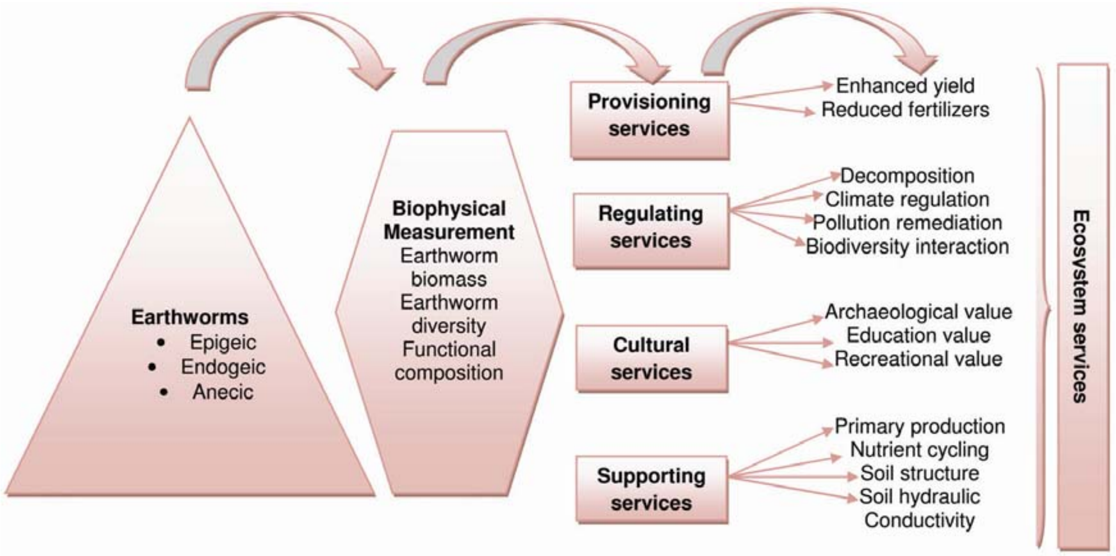

Figure 1. Ecosystem service cascade linking biophysical measurements of natural capital with ultimate benefits to society[64].

endogeic earthworm, *Reginaldia omodeoi* was reported to increase soil bulk density from 1.24 to 1.31 g cm^{-3} and from 1.37 to 1.48 g cm^{-3} in two different studies[12]. A significant increase was also observed in bulk density from 1.12 to 1.23 g cm^{-3}. A resulting decrease in porosity from 58 to 53% in the presence of a tropical endogeic earthworm, *Pontoscolex corethrurus* was also observed[13]. In a long-term field experiment under tropical condition, interaction between soil compacting (*R. omodeoi*) and decompacting (small *Eudrilidae* family) species helped in maintaining the soil structure[14]. Earthworms also affect size distribution of soil aggregates. De-compacting earthworms (e.g. *Millsonia anomala*) destroyed the macro-aggregates formed by the compacting ones, whereas compacting earthworms acted similarly with the casts of the de-compacting earthworms[15]. This indicates that there exists a wide variability in the action of earthworms in regulating soil structure dynamics. It was reported that compacting earthworms (e.g. *R. omodeoi*), inoculated under yam and maize culture increased the relative proportion of aggregates >2 mm from 30 to 54% and 25 to 42%, respectively[16,17]. Earthworms are estimated to produce casts at the rate of about 40–100 tonnes ha^{-1} $year^{-1}$ and thus, immensely contribute to the formation of stable soil aggregates[18]. They could convert 18–42% of soil material into macro-aggregates only within two months[19].

It is obvious that earthworms improve soil porosity as well. In a study, fine (<0.4 mm) fraction of soil aggregates was predominant in a treatment with no earthworm population, compared to the treatments where earthworms were present[15]. It was also observed that endogeic earthworms modified soil porosity to control the water flow in the soil, and the effect depended on the equilibrium between cast production and soil degradation[20].

Soil water retention

The dwelling activity of earthworms modifies soil aggregates and increases stable macro-pores[21] which improves water infiltration to the soil. Interestingly, each ecologically distinct group of earthworms has different impacts on soil water flow due to the dissimilar burrowing activity of the groups[22]. A study reported enhanced drying of the topsoil by anecic species *Lumbricus terrestris* and endogeic species *Aporrectodea caliginosa*, while the presence of *Lumbricus rubellus* tended to increase the soil water status[23]. In comparison to other species, *A. caliginosa* helps in enhancing the soil infiltration and faster water movement to the subsoil layers due to its high dwelling activity in the soil.

Earthworms interact with plant species composition of agro-ecosystem. A certain plant functional group along with earthworm biomass could significantly alter the spatial and temporal variations in soil hydraulic properties while soil texture had no impact on such properties[24].

Soil carbon sequestration

Earthworms induce the primary production of ecosystems by enhancing the nutrient release in the soil, thereby contributing to climate change regulation activities[25]. This action could be due to enrichment of organic matter, nutrients and water in the gut of the earthworm species, which encourage microbial activity[26]. These microbial byproducts facilitate in binding the soil particles into stable aggregates[27]. Thus, earthworms help in maintaining a higher C content through the formation of stable aggregate and stabilizing C by preventing its otherwise rapid degradation and loss as CO_2 and/or CH_4 (ref 28). An

Table 1. Role of earthworms in modifying soil physical, chemical and biological properties

Properties	Parameters	Earthworm species involved		Change in the property (% over control)
Physical	Aggregates	*Eudrillus eugeniae*[78]		–19.50 (Micro), –76.97 (Macro)
		Millsonia anomala[79]		71.54
	Bulk density	*M. anomala*[79]		8.029
		Aporrectodea longa, Aporrectodea tuberculata and Bimastos parvus, Phoenicodrilus taste[80]		0.71
	Hydraulic conductivity	*Aporrectodea caliginosa*[81]		8.06
		Lumbricus rubellus[81]		5.44
		Octolasion cyaneum[80]		28.54
	Water holding capacity	*Megascolex megascolex , Eudrilus eugeniae, Eisenia fetida*[77]		61
Chemical	Soil organic carbon	*Pheretima alaxandri*[38]		2.66
		E.eugeniae[78]		27.22
		Pontoscolex corethrurus[82]		21
		Exotic species (*A. tuberculata, Lumbricus terrestris*)[83]		34.81
		A. longa, A. tuberculata and B. parvus, P. taste[80]		64.14
		M. anomala[79]		-1.36
	pH	*Pheretima alaxandri*[38]		10.61
		NA[84]		27.08
		A. caliginosa[85]		5.6
		A. longa, A. tuberculata and Bimastos parvus, Phoenicodrilus taste[80]		-4.54
	Nitrogen content	*E. eugeniae*[78]		50
		P. corethrurus[82]		2.04
		Exotic species (*A. tuberculata, L. terrestris*)[3]		48.52
		A. caliginosa[85]		1.9
		A. longa, A. tuberculata and Bimastos parvus, P. taste[80]		47.11
		M. anomala[79]		-1.51
		Metaphire guillelmi[86]		-28.69
	Phosphorus content	*P. alaxandri*[38]		26.66
		E.eugeniae[78]		72.47
		A. longa, A. tuberculata and B. parvus, P. taste[80]		20.12
		M. guillelmi[82]		-27.11
	Potassium content	*P. alaxandri*[38]		80.66
		E. eugeniae[78]		64.07
	Sodium content	*A. longa, A. tuberculata and B. parvus, P. taste*[80]		3.64
Biological	Microfauna	NA	Bacteria[87]	26.25
			Fungi[87]	17.39
			Actinomycetes[87]	15
		A. caliginosa	Protozoa[88]	-18.24
			Rotifers[88]	-90
			Nematodes[88]	-83.80
		P. corethrurus	Nematodes[89]	-20.60
		NA	Azotobacter[90]	93.16
	Soil organic matter	NA[6]		26.22
	Enzymatic activities	NA	Cellulase[87]	8.73
			Amylase[87]	57.82
			Invertase[87]	79.87
			Urease[87]	18.67
			Protease[8]	20
		A. caliginosa	Cellulase[88]	-17.2
			Dehydrogenase[88]	79.26
			Protease[88]	98.27

Table 2. Role of earthworms in CO_2 and N_2O emission from the soil

Continents	Country	Emission (mg kg^{-1}) CO$_2$	N$_2$O
Asia	China[27]	1079.8	0.4227
America	Canada[65]	340.0	0.105
	Canada[66]	2568.0	0.818
	Mexico[67]	11.3	2.600
Europe	Netherlands[68]	881.0	0.056-0.789
	Netherlands[69]	473.9-593.6	1.397
	Netherlands[70]	302.0	0.973
Africa	Antsirabe, Madagascar[71]	48.0	3.800
Oceania	Australia[72]	1510.6	1.055

increase in soil organic C from 16.1 to 17.9 g C kg^{-1} and from 12.4 to 14.7 g C kg^{-1} after the introduction of *Lumbricus terrestris* to a chisel-tilled soil under maize-soya bean rotation has been reported[29].

Increase in C emission from fields with a good earthworm population was also widely reported (Table 2). A meta-analysis indicated that although earthworms sequester C in macro-aggregates, it also increases CO_2 emissions by 37% through aerobic respiration[30]. A decline in organic matter from an arable land with high earthworm population was recorded after 15 years[31]. It appears that earthworms can stabilize the soil organic matter when organic residues are regularly added to the soil[32]. Addition of organic matter is recommended rather than the inoculation of earthworms into the soil al one, to improve the soil fertility in the agro-ecosystem[33]. A majority of Indian soils are low in organic C status, and therefore it is likely that earthworm services can be realized only when organic inputs were added to the soil to encourage soil C sequestration.

Nutrient cycling in soil

A number of studies highlighted the role of earthworms in nitrogen flow in the agro-ecosystem by increasing the nitrous oxide (N_2O) emissions (Table 2). The flux of N by earthworms was estimated at 63 kg ha^{-1} year^{-1} in no-tillage system[34], and 10 and 41 kg ha^{-1} year^{-1} in monoculture and organically fertilized agro-ecosystems[35,36].

Earthworms exhibit profound influence on soil microbial community and increase nitrogen mineralization in soil[37]. However, earthworm effects on N-cycling is determined by cropping system and fertilizer types, and by the predominant species and species interactions in the soil[38]. Therefore the earthworm species and substrate present in the soil largely determine the N-immobilization and/or N-mineralization[39]. Hence, agroecosystem management becomes extremely important[40]. Mineralization of organic substances is assisted through ingestion, fragmentation and transportation of the partially decomposed plant residues by earthworms which increase the availability of nutrients in the soil[41]. Plant growth is improved through increase in nutrient composition in plant tissues[42], and through higher nutrient release in the soil and uptake[43]. Microbial activity is increased in the presence of earthworms, leading to nitrogen-mineralization and immobilization through direct or indirect benefits by earthworms[44].

Earthworms were also reported to increase the availability of phosphorous by facilitating changes in the biogeochemical status of P in burrow-linings[45]. In a pot experiment with earthworms, higher levels of plant available P resulted in increased plant growth from 15.7 to 16.8 g dry biomass per pot[46].

Soil biodiversity interactions

Earthworms are an integral part of the soil ecosystem, and therefore, exhibit intimate functional interactions with microbes. The effect is manifested through three basic mechanisms: comminuting, burrowing and casting, and grazing and dispersal, which change the soil's physico-chemical and biological regimes. Earthworms possibly condition the substrate which promotes microbial activities.

Earthworms induce the nematode population in the soil and nematode tropic structure[47] which help in assimilating amino acids with other compounds[48]. In contrast, *Lampito mauritii* decreased the numbers of nematodes[49]. Micro-arthropod population in soils e.g. *Collembola* in soils was increased in the presence of earthworms[50]. Micro-arthropods get attracted by earthworms through their action on surrounding soil, where water availability, aeration and pores size are improved[51].

Pollution remediation

Earthworms are reported to bio-accumulate high concentrations of heavy metals like Cd, Hg, Pb, Cu, Mn, Ca, Fe

Table 3. Heavy metal concentration (mg kg^{-1}) in different species of earthworms

Species	Cd	Cu	Pb	Zn
Pheretimaposthuma[73]	0.0498	6.092	0.0173	1.92
Pheretima californica[74]	9.18	74.68	670.55	657.75
Aporrectodea caliginosa[75]	11.6–102.9	17.9–35.9	1.9–182.8	556–3381
Lumbricus rubellus[75]	7.7–26.3	16.0–37.6	0.5–37.9	667.9–2645
Aporrectodea tuberculata[76]	–	361	–	631
Eisenia foetida[76]	–	249		439
Lumbricus terrestris[38,77]	–	39.0	31.0	132
	–	62.0	10110	1550

and Zn in their tissues[52] by ingesting them with soil. This converts ionic state of these metals and make them available for plants after earthworm excretion (Table 3). In a study, higher amounts of heavy metals were found in earthworms collected from the roadside and mining sites[53]. Earthworms accumulate higher amounts of Zn and Cd[54] and reduce the concentrations of Cr, Cu, Zn and Pb to the limits set by USEPA in 60 days using vermicompost sludge (biosolids)[55]. Thus earthworms may be regarded as bio-indicators for evaluation of soil health.

Production enhancement

Earthworm's role in plant growth has been widely demonstrated[43], possibly due to increased nutrient availability in soils. A meta-analysis revealed the role of earthworms in increasing crop yield by 25% and aboveground biomass by 23% (ref. 9). Leaf weight, cob biomass and the number of cobs of maize crop also increased by 40, 152 and 130%, respectively in the presence of *Millsonia anomala*; increased leaf production of rice was recorded by 14% in the presence of *Chuniodrilu zielae*. Association of *M. anomala* and *C. zielae* had better impact than their individual effect[56].

Considerations for economic quantification

Diversity, abundance and biomass are the major parameters to be considered for quantifying the role of earthworms in ecosystem services. We have so far discussed the ecosystem services by earthworms. Here we develop a methodology for quantification and valuation of these services in monetary terms. The methodology covers following five major steps.

Identifying agroecosystem services

Although direct benefits of earthworms are disguised, their contribution to the ecological modification of agroecosystem and to the economy of farmers is well-recognized. Identification of major benefits is the prime step for quantification and valuation of ecosystem services, considering the socio-economic and ecological measures of an individual service.

Developing markets

The next step is to develop the market for identified services. In general, it is crucial to ensure the proximity of the service in terms of land management approach, farmers' intervention (fertilizer and irrigation inputs), human activity, demography and transfer to market cost for generating a service market[57]. Six steps have been identified for creating ecosystem services market: (1) generation of demand; (2) definition of unit and supply; (3) definition and establishment of payment mechanism; (4) establishment of supporting institutions; (5) feedback and environment[58] and (6) stability and conditionality of programme implementation[59].

Assigning monetary values

Stakeholders may assign values to the ecosystem services based on the markets and the discharge of ecological and socioeconomic services. Many studies have given values to a particular service by measuring the earthworm's population in subsoil or topsoil. Earthworm population was used to estimate the quantity of fertile soil annually[60] depending on biomass and soil turnover estimates[61,62] respectively. Besides, at an average earthworm biomass of 75 g m^{-1}, grassland productivity was approximated to US$ 152 million in 2.25 m ha of land[63].

Consideration of external drivers

Once monetary values are assigned, the external drivers (climate change, land-use pattern, *etc*) affecting the soil processes may be considered for cost-benefit analysis. These factors influence the soil processes leading to lesser natural capital stocks.

Trade-off analysis

This is a process of quantifying the relationship between key indicators associated with changes in agro-ecosystems and relevant policies. A meta-analysis indicated that earthworms increase CO_2 emissions rather than its sequesteration[30]. We must take note of these issues which affect policy-making, and influence the stakeholders or decision makers. A trade-off analysis to quantify the indicator's effect on agro-ecosystem and in policy-making is therefore and must be considered.

Conclusions

We need larger and more robust data on soil biodiversity to understand the ecosystem services by soil fauna, i.e. microorganisms and micro-arthropods. The earthworm is an essential component in sustainable agricultural systems, although major gaps remain in understanding their role in providing ecosystem services. Therefore, there is a need to identify all the ecosystem services provided by each ecological group of earthworms along with other soil biota. The existing and new knowledge on earthworms and related ecosystem services need to be integrated. Additionally, the farm-level management practices should be enhanced to promote ecosystem services[64]. Cost-benefit or trade-off analysis must be accounted. It is also necessary to update the knowledge of monetary values generated by earthworm population at local or regional scale for economic evaluation of ecosystem services.

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