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Agro-ecological Role of Earthworms (*Oligochaetes*) in Sustainable Agriculture and Nutrient Use Efficiency: A Review

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

Earthworms which inhabit soils and litter layers in agro-ecosystems play significant roles that regulate soil ecosystem services supporting agriculture. Through their feeding, burrowing and casting activities, earthworms redistribute organic material within the soil, increases soil penetrability, and influence soil organic matter decomposition and nutrient cycling. These activities modify plant root distribution, increase soil microbial activity and influence the supply of plant nutrients. Because earthworms respond quickly to land use changes, farm management practices affect their diversity, abundance and biomasses. While cultivation and use of acidic fertilizers and chemicals reduce earthworm numbers, management practices that enhance the supply of earthworm food such as fertilization and manure application increase their numbers. This article reviews the beneficial earthworm facilitated biotic interactions that enhance nutrient use efficiency in agro-ecosystems. First, earthworm identification, distribution, and ecology together with factors that determine their populations in agro-ecosystems are discussed. It shows that agricultural practices affect earthworms directly and that farm management can be manipulated to encourage

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practices that favour earthworms. Secondly, beneficial biotic initiated ecosystem services resulting from earthworm activities are presented highlighting the significant roles they play in influencing soil processes. Finally, the review ends with recommendations for future research. Overall, this review shows that earthworms are an important resource to be managed for nutrient use efficiency in agro-ecosystems. It also demonstrates the need for further research that links the physical, chemical and biological effects of earthworm activities to plant nutrient supply. It is necessary to develop suitable farm management practices that optimise these beneficial roles.

Keywords: Earthworms; biotic mediated ecosystem services; farming efficiency; agro-ecology; sustainable agriculture; agro-ecosystems.

1. INTRODUCTION

Protection of the soil habitat is the first step towards sustainable management that determine its long-term quality and productivity. However, very little is known about the organisms that live in the soil and their roles in the functioning of the soil ecosystem. The role of earthworms in soil fertility is known since 1881, when Darwin (1809–1882) published his 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 contribution of soil organisms in ecosystem functioning [1]. Earthworms are a major component of the soil fauna community in most natural ecosystems and comprise a large proportion of the macrofaunal biomass [2]. In cultivated soils, where organic matter is frequently related to fertility and productivity, the invertebrate community especially earthworms play an important role in soil organic matter dynamics by regulating the mineralization and humification processes [3,4].

Earthworms are divided into three ecological categories based on their colour; body size and shape; location within the soil habitat; burrowing ability and food preference [5,6, Table 1]. The anecic species that build permanent vertical burrows into the deep mineral layers of soil; the endogeic species that build extensive horizontal but non-permanent burrows in the upper mineral layer of soil and the epigeic species that live on the soil surface where they ingest litter and humus [7,8]. In the majority of habitats and ecosystems, it is usually a combination of these ecological categories which together or individually are responsible for maintaining the fertility of soils [9].

The ecosystem services of earthworms include: soil formation, nutrient cycling, crop production, carbon sequestration, detoxification, protection of plants against pests, water infiltration and storage [10-14]. Earthworms traditionally have been considered convenient indicators of land use and soil fertility. Their relatively large size, ranging from 1 to 80 cm or longer, slow displacement in soil and re-colonization make them easy to capture and sort. These features render them attractive as bioindicators [15]. Agricultural management practices such as tillage, crop rotation, stubble retention, drainage, irrigation, lime, fertilizer and slurry application, pesticide use and stocking rate can influence Oligochaeta communities [6,16,17].

In agriculture, the beneficial effects of earthworms could help to overcome major issues like compaction by alleviating soil structure degradation. When organic amendments are applied, earthworms could boost organic matter mineralization thereby improving nutrient availability. Moreover, nutrient release due to earthworm activity is temporally and spatially synchronized with plant activity [18]. Indeed, through the creation of earthworm casts enriched in mineral nutrients, they could contribute to enhanced nutrient use efficiency and decrease the risks of nutrient leaching. Integrating earthworm activities with the functioning of above ground systems will increase the farming efficiency of agro-ecosystems for continued human well-being [19,12]. This review discusses at first the identification, ecology and farm management impact on earthworm communities. It then discusses the ecosystem services provided by earthworms in agro-ecosystems that enhance agricultural sustainability and productivity. These discussions are based on examples rather than an exhaustive review of literature.

Table 1. General behavioural and morphological characteristics of earthworm functional groups

Characteristic	Epigeic earthworms	Endogeic earthworms	Anecic earthworms
Habitat	Surface dwellers	Upper organic rich soils	Deep burrowing
Main food source	Plant litter and humus material at surface	Organic mineral soil	Plant litter at surface and soil
Burrow formation	Remain active in the surface	Horizontal burrows	Vertical burrows
Microbial communities in burrows	Not applicable	Evidence of relationships available	Positive relationships
Cocoon production	Highest	Moderate	Low
Life cycle	Short	Moderate	Long
Body length at maturity	≥ 100 mm	50 – 100 mm	≤ 150 mm
pigmentation	Highly pigmented	Un-pigmented	Anterodorsal pigmentation
Main activities	Facilitate litter comminution and the breakdown of organic material at the surface	key role in soil aggregate formation	influence decomposition and nutrient cycling by incorporating surface litter into the soil profile
Examples	*Dendrobaena octeadra* (Savigny, 1826) and *Lumbricus rubellus* (Hoffmeister, 1843).	*Aporrectodea calignosa* (Savigny, 1826), and *Octolasion cyaneum* (Savigny, 1826).	*Lumbricus terrestris* (Linnaeus, 1758) and *Aporrectodea longa* (Ude, 1885).

2. EARTHWORM IDENTIFICATION, DISTRIBUTION AND ECOLOGY

About 3000 species of earthworms are found worldwide. Major families are found particularly in specific continents. Adult earthworms are identified based mainly on the clitella position, shape, setae and internal organs. Different countries have manuals for earthworm identification (e.g. [20] for France, [21] for Italy, [22], for United Kingdom, [23] for New Zealand and [24] for India). Earthworms vary greatly in length [viz., *Microscolex phosphoreus* (Duges, 1837) and *Dendrobaena octaedra* (Savigny, 1826) are around 20 mm long, while *Drawida grandis* (Bourne, 1894) may be one meter in length and *Megascolides australis* (McCoy, 1878) can grow up to three meters. Asiatic species from Mekong depositions can be several meters long [25]].

The most effective field techniques for earthworm collection and enumeration are hand sorting, heat extraction with kempson apparatus and wet sieving of soil [26,27]. Another method is the use of chemical extractions such as formalin or mustard oil [28]. This method is efficient for sampling anecic species with burrows opening directly to the surface. It is not suitable for collecting endogeics species that don't surface easily or epigeic species that can move laterally away from the sampling area in response to the chemical [29,30]. Finally, electrical extraction which requires specialised equipment [31] with the advantage of causing minimal disturbance to the soil [32] can be used.

Earthworms inhabit diverse niches. Majority of earthworm species live in the soil, except some species like *Pontodrilus burmudensis* (Beddard, 1891) which lives in estuarine water. Besides, they are also found in organic materials like manures, litter, compost, hydrophilic environments near fresh and brackish water and also in snowy patches. Most earthworms are omnivorous; although some species such as Agastrodrilus genus from the Ivory Coast of Africa (e.g. *Agastrodrilus multivesiculatus (*Omodeo and Vaillaud, 1967) has been reported to feed upon other earthworms of the family Eudrilidae [33].

3. AGRO-ECOSYSTEMS AND MANAGEMENT OF EARTHWORM ACTIVITIES

Agricultural intensification leads to the loss of biological diversity and the associated natural services they provide [34]. This results in ecosystems that require addition of external inputs for their maintenance. Example is the alteration of the decomposition process as a result of plant harvesting leading to the maintenance of soil fertility not through nutrient cycling but fertilizer application [35]. The challenge is to develop ways of increasing farm productivity that benefit farmers while conserving and regenerating the natural resource base [36]. Earthworm activities influence soil-based processes which promote soil ecosystem services, nutrient use efficiency and agricultural productivity [7,37-39]. Therefore, incorporating these activities into agro-ecosystem management can provide key ecological strategies for their sustainability and nutrient use efficiency. For this to be realised, it is necessary to understand the structural modifications in earthworm communities arising from agricultural practices.

Earthworm abundance is determined by food supply, therefore, agricultural practices which affect the nature and type of organic material returned into soil, determine their density and biomasses [16,40-42, Table 2]. Similarly, landscape transformations may lead to changes in earthworm distribution and abundance [43-45]. Their optimum existence and survival depends on adequate soil moisture, temperature, texture, pH, electrolyte concentration, and sufficient food sources [46-48]. Creating conducive environments at landscape and plot level can enhance them and the ecosystem services they provide. Highlighted below are some of the activities that affect earthworms in agro-ecosystems.

3.1 Tillage

Unlike reduced or no tillage systems that provide stable environments, the physical disturbance associated with tillage disrupts the soil habitat [49,50], thereby reducing soil organisms including earthworms. Predation by ravens, sea gulls and other vertebrates during and after tillage may worsen these population decline [51]. Conversely, crop residue left on the soil surface of non-tilled fields reduce runoff, increases soil organic matter content, improves aggregate stability, provide earthworms with food and insulate them from desiccation and predation [44,52,53]. Fields under no-tillage exhibit higher earthworm numbers than tilled fields (Table 3). Tillage physically destroys earthworm burrows, cocoons, and the earthworms themselves. The large burrowing species such as *Lumbricus terrestris* (Linnaeus, 1758), *Aporrectodea longa* (Ude, 1885), *Octodrilus spp*. and the surface dwellers are the most affected. Nevertheless, restricting tillage to the uppermost part of the soil can preserve earthworm populations [54]. The effects of drastic reduction of numbers is felt after repeated tillage events (Table 3).

3.2 Fertilization and Organic Inputs

Application of organic material such as animal manure and sewage wastes onto soils increases earthworm abundance and activity [5,16,55,56]. Nonetheless, applying high quantities of liquid manure such as pig slurry negatively affect earthworm densities in both grassland and cultivated soils [55,57]. Mulching supports a higher population of earthworms by providing nutrients and a conducive micro climate [58]. This affects mostly the surface feeding earthworms. For example [59] demonstrated that in the absence of mulch, soil froze much faster and increased earthworm mortality because of their inability to adjust to the decreasing temperatures.

The use of inorganic fertilizers lead to disruptions of normal soil functioning because they change the energy, nutrient cycling and storage in soils [60]. With an increase in nutrient availability, earthworm numbers and biomass too increase [61,62]. This increase is attributed to enhanced organic residues resulting from increased plant biomass production [63,64]. For example, earthworm numbers reported in meadows receiving inorganic fertilizer were almost twice as those in unfertilized meadows on a Georgia piedmont [65]. Nevertheless, very high fertilization impacts negatively on earthworms [63,66], especially when soils become acidic [40].

3.3 Direct Inoculation

Earthworm populations can be increased by direct introduction of live worms or cocoons to maintain their populations and to benefit soil productivity. Here, care must be taken to ensure their establishment after the inoculation e.g. from limited food availability, emigration or competition from other soil organisms. Earthworm dissemination has been implemented in order to improve productivity in New Zealand and Australia [67], and in reclaiming polders in the Netherlands [68]. In fact earthworms can be introduced into new ecosystems. Prior to these introductions, their effects to natural ecosystems should be established because introduced earthworms can have deleterious effects on indigenous ecosystems [69,70]. For example, the introduction of an anecic species into Australia, from France, has been highly criticized [71] while earthworm invasion has resulted in the reduction of the thickness, heterogeneity and organic matter content of in forest soils [72,73].

3.4 Chemicals e.g. Pesticides and Herbicides

Chemicals are harmful to earthworms when applied either directly to the soil or indirectly from treated plants [74,75]. Herbicides have a less direct impact on earthworms [64] although some can be highly toxic [76] resulting in a negative impact on earthworms due to reduced vegetation cover. Fungicides such as copper and zinc residues from copper sulphate and carbamates, organophosphates and many fumigants and contact nematicides are highly toxic to earthworms [74,75,77]. Earthworms are however not impacted by natural and synthetic pyrethroids [74,78].

Table 2. Agricultural management practices that influence earthworm densities and biomasses

Remarks	References
Greater numbers found in organic farms than in conventional farms.	[79, 80, 81].
Greater numbers found in no-till fields.	[82, 83].
Alley cropping increases field earthworms numbers	[84].
Vegetative field margins (windbreaks, shelter beds, or hedgerows), serve as refuges to maintain high earthworm numbers in nearby fields.	[85, 86].
Cover crops, especially legume, or legume-grass rotations increase earthworm populations.	[80].
Intercropping systems, especially legume-based intercrops increase earthworm populations.	[87].
Compost, fertilizer and manure applications increase earthworm numbers.	[15,16, 56, 88]
Crop rotations restore earthworm numbers after production of root crops requiring deep cultivation.	[88].
Higher earthworm numbers in irrigated fields.	[16, 17, 42, 89].
Higher earthworm numbers in mulched fields.	59
Chemical applications to soil harm earthworms.	[74, 75].
Direct introduction of life worms or cocoons increases earthworm populations.	[67, 68].
Grassland or pasture systems contain greater earthworm abundances than croplands.	[90, 91].
Urbanization, intensive conventional agriculture and unsustainable forestry practices reduce earthworm diversity and abundance.	[92, 93].
Higher abundances and biomass in fertilized pasture than unfertilized native pasture.	[94].
Reduced worm numbers in high stocking densities.	[95].

Table 3. Research findings on earthworm measurements following field tillage

Remarks	Reference
Non-tilled soils have higher earthworm densities than tilled fields	[83]
Ploughs that restrict tillage to the uppermost part of the soil preserve earthworm populations than mouldboard ploughs	[54]
Earthworms reduced by 70% after five years of soil tillage	[64]
Earthworms were 11-16% of the original grass field after 25 years of conventional tillage	[64]
When compared with tilled fields, there were 30 times more earthworms in no till fields	[63]
2400 earthworm casts m^{-2} in no till fields while there were only 100 casts m^{-2} under conventional tillage	[96]
967 earthworms m^{-2} in no till against 149 earthworms m^{-2} in conventionally tilled fields	[97]

3.5 Heavy Metals

Heavy metals enter the soil from different sources such as fertilizers, pesticides, organic and inorganic amendments, wastes and sludge residues. Once in the soil, they affect earthworms both in their abundance and species responses. For example [98] observed that treatment of orchards and vineyards with copper sulphate strongly affected earthworm density and biomass.

3.6 Land Use Change

Urbanization, intensive conventional agriculture and unsustainable forestry practices are examples of land use changes that can have effects on earthworm diversity and abundance. As the intensity of soil disturbance increases, the abundance of earthworms decreases [92]. For example, in slash and burn practices where trees are replaced with a monoculture, vegetation cover loss corresponds to a similar loss in soil fauna [93,99].

3.7 Other Activities and Factors

Changes that affect the soil habitat directly can consequently affect earthworm diversity and abundance. These include trampling [100], which compacts soil thereby altering its hydrology and biotic composition and invasive species that affect soil chemical and physical parameters and consequently the abundance and distribution of earthworms [101]. Other factors that disrupt soils and affect earthworms either directly or indirectly include: soil erosion, crop rotation, direct and indirect interactions with plants and soil physical and chemical properties [44,88,102,103].

4. ECOSYSTEM SERVICES PROVIDED BY EARTHWORMS IN AGRO-ECOSYSTEMS

Soil-based processes are grouped into four categories: (i) decomposition of organic matter (ii) nutrient cycling (iii) maintenance of soil structure and (iv) suppression of soil-borne diseases and pests [104,105]. Maintaining and improving these soil processes is necessary for the sustainability of agro-ecosystems [106]. Through their actions on the physical, chemical and biological constituents of soil, earthworms play significant roles that drive these processes [107-109]. In agricultural systems, these processes play key roles in mediating soil ecosystem services that have positive effects on nutrient use efficiency and agricultural productivity. These ecosystem services are summarised in Table 4 and include:

4.1 Nutrient Cycling

When earthworms crush and grind litter, they activate soil microbial activities [110] and enhance the mineralisation and humification of soil organic substrates and organic matter incorporation into the soil [111-116]. Earthworms also produce substances such as root exudates, earthworm mucus and saliva [117] that have an effect on microbial selection [118].

Earthworms play a role in soil carbon stabilization by creating soil aggregates that bind and contain carbon [39,114] which is made unavailable for further decomposition [119]. This conversion of carbon sources into stable and resistant forms that decompose less, slows down the release of CO_2 into the atmosphere [119]. Further, the biogenic structures created by earthworms may act as incubators of microbial activities for carbon and nutrient sequestration [112]. Earthworms also take away the easily available carbon from microorganisms thereby increasing the effectiveness of nitrogen and phosphorus mobilisation [39,120].

In spite of these positive roles of earthworms in nutrient cycling, a reduction of the total carbon content in plots inoculated with the earthworm *Pontoscolex corethrurus* (Muller, 1856) has been observed [121,122]. Other studies have demonstrated an increase in phosphorus leaching and decrease in phosphorus availability [123,124] and reduced total carbon and nitrogen [17] on plots dominated by *Lumbricus rubellus*. This species lives and feeds at the soil surface [6] where it can potentially enhance litter decomposition and mineralization thereby accelerating nutrient losses.

Another potentially detrimental effect of earthworm presence is their contribution to emissions of greenhouse gases. Earthworms have a capacity to fragment and mix soil organic matter, mineral particles and soil organisms [41,125]. This enhances the mineralization process that transforms organic compounds into inorganic ones facilitating nutrient losses in the form of CO_2 and N_2O [126-130]. The earthworm gut also offer an ideal microclimate for N_2O producing microorganisms by providing abundant substrate, anaerobic conditions, suitable pH and a high moisture content [131,132].

Table 4. Potential influence of earthworms in regulating soil processes for ecosystem functioning

Key soil process	Earthworm activity	Remark	References
Soil formation	Burrowing, feeding and casting	Earthworms breakdown primary minerals and incorporate organic matter into the soil.	[133,134].
Soil structure	Burrowing, feeding and casting	The interaction of soil water, organic matter, and earthworm activities determine how soil particles and pore spaces are arranged. Earthworms remove dead material, loosens soil, provides an enriched layer of cast soil, and recycles organic wastes and nutrients.	[37,135,136,137,138].
Soil porosity and Water regulation	Burrowing	Macro pores created by earthworms can modify soil porosity and thereby affect water regulation.	[139,140].
Erosion control	Burrowing	Increased infiltration rate associated with earthworm burrows decrease soil erosion and minimise surface runoff.	[141,142].
Nutrient cycling	Feeding, burrowing, casting, activation of microbial activity and enhanced mineralisation and humification of organic substrates	Earthworms accelerate rates of organic matter breakdown and stabilisation, increase soluble nutrient content and shift the same into deeper soil layers; thus they contribute to nutrient turnover.	[119,143,144,145].
		Earthworms take away easily available carbon from microorganisms thereby increasing the effectiveness of nitrogen and phosphorus mobilisation.	[120]
		Earthworms chemically alter microbial substrates during the decomposition process thereby enhancing microbial activity.	[107,109].
Physically transforming the soil environment	Burrowing	When earthworms feed on the soil substrate, they: (i) transform it physically; (ii) maintain and improve its structural porosity, aggregation, drainage, aeration, water infiltration and retention; (iii) enhance root growth and penetration and; (iv) bring deeper soil to the surface. These activities are important in restoring degraded soils and ameliorating effects of soil compaction and improving soil structure	[17,114,119,146,147,148,149,150, 151,152].

Table 4 continued....

Key soil process	Earthworm activity	Remark	References
Primary production	Decomposition, burrowing, feeding and casting	Earthworms have been related with significant increases in primary production.	[38,67,153,154].
Facilitation	Feeding, burrowing, decomposition and relationships with other soil fauna	Earthworms: (i) transport soil microbes and other materials within the soil matrix; (ii) modify soil organic matter, microbial and invertebrate communities e.g. increase of beneficial mycorrhiza populations; (iii) are an important food source for other organisms; (iv) provide plant protection against pests and diseases (v) enhance plant succession (vi) produce exudates, mucus and saliva; activities that affect soil carbon and nitrogen dynamics, contribute towards a rich soil food-web and impact soil microbial selection in the soil.	[37,117,118,129].
Carbon sequestration	Decomposition, burrowing	Earthworms conversion of carbon sources into stable and resistant forms that decompose less slow CO_2 release into the atmosphere. The biogenic structures they create act as act as incubators of microbial activities for carbon and nutrient sequestration.	[119,155,156].
Soil stability	Casting	Earthworms ingestion of large amounts of soil and organic residues create stable soil aggregates.	[157].
Decomposition	Burrowing, feeding, and interactions with soil microbes	Earthworms break down and incorporate organic residues into the soil by fragmenting soil organic matter, stimulating microbial activity and transforming organic compounds into inorganic ones that are assimilated by plants.	[113,114,115,116,158,159].
Impact on soil parameters	Feeding, burrowing and decomposition	These earthworm activities lead to changes in soil chemistry, microflora, microarthropods and vegetation.	[69,70,160].
Seed dispersal	Feeding and burrowing	Earthworms promote plant regeneration by ingesting viable seeds which they later deposit in their casts.	[161,162].

4.2 Plant Growth and Productivity

Earthworm activities on plant production and their impact on soil seed banks and seedling recruitment [162] have a potential of increasing the sustainability of agro-ecosystems [6,153,163,164]. For example, by ingesting and depositing viable seeds in their casts within the soil profile or at the surface, earthworms promote plant regeneration [161]. Thus, they play a role in vertical seed movements; may alter the composition of the soil seed bank or constitute a regeneration niche for these plant species [165].

4.3 Soil Formation and Physical Characteristics

The physical transformation of soil by earthworms [166] through burrowing and casting activities maintain and improve its structural porosity [60,146] and aggregation [148,167]. These activities improve nutrient cycling and availability, soil drainage and aeration, water infiltration and retention, root penetration and soil formation [160,168,169,170,171]. Their effect on surface roughness decreases surface runoff but enhances water infiltration [172] while their pores allow soils to store much water [147]. These earthworm activities on soil water, air and root dynamics play important roles in regulating soil processes and nutrient cycling [173] that can modify microbial and soil invertebrate communities at different scales [174,170]. Despite these positive earthworm effects on soil structural properties, the endogeic earthworm *Pontoscolex corethrurus*, has been claimed to be responsible for soil compaction in potato cultures [175] maize fields [176], and in Amazonian pastures [177].

5. EARTHWORMS AS SOIL QUALITY INDICATORS

Earthworms are important soil organisms that are sensitive to ecosystem changes and rehabilitation [87,178,179,180]. Because of their large size (1 to 80 cm or larger [181]), limited movement, straight forward taxonomy and slow re-colonisation, they are easy to collect and measure. This makes them attractive as potential tools for ecosystem monitoring [6,52,64]. Simple evaluation of numbers or biomass can give useful and sufficient information aimed at detecting soil quality trends in time and space [182]. In fact a biological soil quality index (QBS-e) based on earthworms, has been developed to compare environmental quality [183]. This is done by determining: (i) their abundance, biomass and species composition; (ii) their behaviour when in contact with the soil substrate; (iii) chemical accumulation in their bodies and (iv) their biochemical and cytological stress biomarkers in relation to land use. Earthworm casts and the amount produced can give an index of assessing earthworm activity while the presence or absence of the sensitive species can serve as an indicator of environmental degradation or rehabilitation. Studies on the pressures on earthworms by human activities have shown that earthworms are best indicators of heavy metals, toxic pollutants, and anthropogenic changes in soil [162,184-190].

6. RECOMMENDATION FOR FURTHER RESEARCH

This review has shown that incorporating the functional roles of earthworms in agro-ecosystem management is key to sustainable agriculture. There is need for research that links earthworm activity, their ecological functions and ecosystem services they provide in agro-ecosystems. These research should emphasise on technological developments that optimise earthworm functional roles in agro-ecosystems more so those that connect earthworm activity and plant productivity. It should focus on the management and monitoring of earthworms and knowledge of these linkages to farm management initiatives and policies. The challenge is to develop tools that; (i) illuminate earthworm roles; (ii) integrate above ground and below ground systems; (iii) match farmers' goals, aspirations and constraints, and (iv) offer opportunities for application.

Earthworm measurements offer valuable information to assess management effects. However, appropriate monitoring tools that link earthworm data to soil processes are missing. Experimental research is necessary to develop these tools, provide information on the monitoring and valuation of ecosystem services in agro-ecosystems and which groups could be nurtured to provide specific ecosystem services. These requires in-depth research to understand their functional roles in the assessment of nutrient dynamics relative to earthworm measurements. The technology should be applicable to farmlands for increased nutrient use efficiency. The direct and indirect effects on earthworm communities from agro-ecosystem alterations due to climate change and land management practices should be established.

New research should integrate new and existing methodological approaches that link earthworm roles with soil processes under field conditions and conceptualise the same under different scales. These cases call for the development of agro-ecological technologies which emphasize the conservation and regeneration of earthworm diversity that meet the contemporary socioeconomic and environmental challenges.

7. CONCLUSION

The linkages between earthworm activity and agricultural productivity are numerous, interrelated, and in many cases result in ecosystem service provision. With their peculiar habits of feeding, burrowing, casting, etc., earthworms provide opportunities that can be utilised to enhance nutrient use efficiency in agro-ecosystems. Thus, earthworms have a potential to contribute to the management of soil fertility for plant growth, enhanced farming efficiency and agricultural sustainability. For this to be realised, it is important to understand the roles they play in driving soil based processes, their biology and ecology.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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