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Earthworms and Agricultural Systems Management: Emphasis on the Latin American Region

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ABSTRACT

The study of earthworms in Latin America is crucial for promoting the sustainability of this region. In the past 30 years, the tropical forests of Latin America have been exposed to deforestation rates greater than 100,000 ha yr^{-1} (in the case of Mexico), which will result in the loss of biodiversity of plant species and the micro- and macrofauna of the soil. By biomass, earthworms are the main macrofauna group in tropical forest soils. Although a significant amount of research has been conducted on the ecology of earthworms in the natural ecosystems of the region, there are still large geographical areas that lack adequate descriptions of the diversity of the endemic earthworms. Indeed, there has been an increase in research interest with regard to agricultural systems, specifically in relation to earthworm ecology and its connection with agricultural systems that are designed to reduce erosion, increase the organic matter content in the soil and ensure the reproduction of micro- and macrofauna. However, in this topic the advances in research on earthworms in Latin America have been sporadic. Therefore, this field of research and agricultural development should be steadily promoted. In this review, we outline the further investigation that is required in Latin America with regard to the following topics: (a) the relationship between tillage and cropping systems and earthworm populations, (b) the cumulate effects of pesticides and heavy metals on the earthworm life cycle and (c) the linkage between the organic substrate quality and earthworm dynamics and processing of nutrients.

Keywords: agricultural practices, crop rotation, earthworm diversity, earthworm populations, irrigation, tillage
Abbreviations: C:N, carbon-nirogen ratio; **CT**, conventional tillage; **GHG**, greenhouse gases, **MT**, minimum tillage; **NT**, no tillage; **SOM**, soil organic matter

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INTRODUCTION

Earthworms belong to the group of macro-invertebrates that live in the soil and participate in the soil function through the creation of bio-structures (Jiménez *et al.* 1998). The greatest diversity of earthworm species occurs in natural ecosystems, particularly savannahs and rainforests (Decaëns *et al.* 2004). When natural systems are converted for agricultural and livestock use, major changes in the structure of the vegetation and the habitat of the original systems occur, giving rise to a new balance. It has been found, for example, that upon changing land use from grassland savannah to pastures, the diversity of the native earthworm species remained intact, together with an increase in the biomass and population of the individuals (Decaëns *et al.* 2004).

In contrast, the deforestation of tropical rainforests (the Amazon, for example) and a change in land use to agriculture represent a drastic change in the composition and diversity of earthworm populations and a strong trend toward dominance of one or a few peregrine species (Decaëns *et al.* 2004).

The main objectives of this review were the following: 1) to document the dynamics of the species diversity, population density and biomass of earthworms in agricultural and natural ecosystems, focusing primarily on the Latin American region, 2) to analyse in-depth the effects of different agricultural management systems (tillage systems, rotation, and crop residues management) in the dynamics of earthworm populations and 3) to review the use of earthworms as an indicator of the soil quality and the role of earthworms in the emission of greenhouse gases.

We found that the study of earthworms in the natural and transformed ecosystems of Latin America have benefited from the existence of an international network of specialists who have been able to share theoretical approaches and methodologies and have worked extensively in the dissemination of knowledge through the organisation of academic events, exchanges with common academic peers, the shared direction of theses, and joint publication of the results. These relationships have allowed comparisons among different situations and the expansion of knowledge. The

Received: 10 May, 2011. Accepted: 26 August, 2011.

Invited Review

bibliography that accompanies this review includes a sample of this scientific cooperation. The current review adds to previous studies related to the benefits of earthworms and focuses on the Latin American experience. Recently, Rivera *et al*. (2009) reviewed the use of vermicompost as a plant growth promoter and an alternative mean to suppress crop diseases.

At the end of the review, we discuss the trends of research in Latin America and the link between the research questions and the emission of greenhouse gases, as well as the use of earthworms as indicators of sustainability in cropping systems.

EARTHWORMS AND LAND USE CHANGES IN LATIN AMERICA

A change in the land use of natural ecosystems, specifically tropical ecosystems to agricultural systems, can cause land degradation in physical, chemical and biological properties. In the latter cases, a significant reduction in the biodiversity of earthworm species tends to occur (Decaëns *et al.* 2001a). Soil fauna, including earthworms, are sensitive to changes in the soil, climate and management systems and induced changes in microclimatic conditions (Hendrix and Bohlen 2002; Jiménez and Decaëns 2004).

An important problem in Latin American agriculture and land use is that human action has led to the introduction of species of earthworms that may or may not coexist with native species in some types of agroecosystems (Falco *et al.* 2007).

Changes in land use in Latin America have had negative effects on earthworm populations. Therefore, it is important to identify approaches to the mitigation and remediation of the problem. Rousseau *et al*. (2010) evaluated various alternatives for the management of crop residues in crop fields and pastures. Their study examined selected agroecosystems with and without crop residues present, and the study also evaluated the option of burning the residues. The authors concluded that the presence of residues mulch improved soil quality and produced a larger population of earthworms. The authors proposed an index to indicate the health of the soil macrofauna.

Earthworm research in the tropical rain forests of Amazon

According to Lavelle and Lapied (2004), the earthworm fauna of Amazonia may comprise up to 2,000 species, taking into account that only has been described one of the major areas of the region. Christoffersen (2010) noted that more than half of the oligochaete taxa of South America are found in Brazil (424), followed by Argentina (208), Ecuador (163) and Colombia (142). The author showed that much more basic research on the taxonomy of oligochaetes is needed in South America.

Peregrine species, mostly exotic, tend to eliminate native species. It is, therefore, likely that the deforestation of the region will result in the elimination of many species. In addition, a change in land use promotes the invasion of new species of earthworms, which can affect the soil conditions, such as when compacting earthworm species replace the native riparian species that act in decompacting of the soil (Hallaire *et al.* 2000). It has been shown that *Pontoscolex corethrurus* is invasive in the area of the Amazon, and the proliferation of this species has increased in deforested or disturbed areas that have been converted to cropland or pasture (Nunes *et al.* 2006; Rossi *et al.* 2010). Marichal *et al.* (2010) have agreed that *P. corethrurus* is strongly associated with anthropogenic systems; their results have shown that this species was found mostly in grasslands and agricultural systems and rarely in forests yet was found to coexist with native species, especially in grasslands and plantations. The authors further argued that the change in the land use in Colombia has affected the community structure of earthworms, a minor phenomenon in the soils of the humid tropics of Brazil; however, they argued that *P. corethrurus* has been established in Colombia for 40 to 60 years and only 10 to 15 years in Brazil. In addition, Marichal *et al.* (2010) considered that this species did not compete with the native species in natural forests, concluding that, in tropical areas where deforestation was destroying the habitat of native species and creating new conditions, the species most easily adapted was *P. corethrurus*, whereas the native species did not prosper in the new habitat.

Brown *et al*. (2006) reviewed the exotic earthworms, both invasive and peregrine, in Brazil and their impact on vegetation and soil. The authors found that approximately 83% of earthworm species are native and 17% exotic. Invasive species can have positive or negative effects on the processes occurring in the soil and on the characteristics of the soil. The types of effects that are found will depend on the type of system that is considered. Brown *et al*. (2006) reached conclusions consistent with those of Marichal *et al.* (2010), who established that *P. corethrurus* promotes the improvement of soil structure and the availability of some nutrients in agroecosystems. However, this same species invades areas that have been converted from forest to pasture. In these areas, it produces negative effects by sealing the soil surface and by reducing the macroporosity of the soil. These changes interfere with the movement of water through the soil. By doing so, they increase the activity of anaerobic processes and cause the release of methane. Brown *et al.* (2006) stressed the importance of knowledge about the activities of native and exotic earthworms in the soil. This information is needed to clearly determine the effects of the earthworms on the ecosystem and to identify earthworm species that can serve as indicators of such ecosystem properties as resistance and resilience to disturbances caused primarily by human activities. These authors emphasised the importance of the movement of materials (e.g., soil, plants). Earthworms may be transported in these materials from one site to another.

It is well known that deforestation results in losses in the chemical and physical quality of the soil (Cerri *et al.* 2004) together with a reduction and loss of soil biota, including earthworms (Barros *et al.* 2001). Righi (1998) studied the response of earthworm populations to drastic changes in habitat in Minas Gerais, Brazil. The author found three species that are endangered by habitat alterations: *Fimoscolex sporadochaetus* Michaelsen 1918, *Rhinodrilus alatus* Righi 1971, and *Fafner rhinodrilus* Michaelsen 1918. James and Brown (2010) considered the possibility that other species of worms are in danger of extinction in different regions of Brazil owing to habitat alterations. They suggested that it is not sufficient to make an inventory of the characteristics of endemic species and their ability to adapt to new conditions; in-depth studies of the relationships of these species with exotic species are also necessary.

Some studies have shown that land use changes affect the structure and density of earthworm communities (Fragoso *et al.* 1997; Jiménez *et al.* 1998); one indicator of this change is the quantity and quality of the biostructures in the soil (Rossi and Nuutinen 2004). In a study in the humid tropics of Brazil, measurements of the soil biostructures demonstrated a high impact of deforestation on the surface-casting activities performed by the earthworm, *Andiodrilus pachoensis* (an anecic species) (Thomas *et al.* 2008). Moreover, a comparison of the density of individuals and the total earthworm biomass produced in the forest and the pastures established after deforestation has revealed that the highest values of both parameters were found in the forest soil and that a lower density of earthworms was found in the pasture.

Several reports have outlined the beneficial effects of earthworms on soil structure. However, under some conditions, earthworms can cause land degradation. In the Central Amazon in oxisol soils in pastures, the casts produced by the highly dominant species *P. corethrurus* (Oligochaeta, Glossoscolecidae) caused a reduction in macroporosity and resulted in increased soil surface crusting (Chauvel *et al*. 1999). However, in a study in the Peruvian Amazon, Hallaire *et al*. (2000) showed that compaction by earthworms depended on soil conditions. In this study, *P. corethrurus* was inoculated in soil with and without crop residues. In soils without residues, the earthworm activity generated crusts on the soil surface and increased the compaction of the soil. As a consequence, the connectivity of the pore network in the soil decreased. In soil with residues, the pores became increasingly interconnected, and no soil compaction occurred. This study indicated that earthworm activity creates soil compaction only if no crop residues are allowed to remain, whereas aggregation occurs in soils that receive organic inputs from crop residues.

Earthworms in Colombian savannah

The savannah in Colombia is a tropical ecosystem with high biodiversity that is threatened by changing land use: the native vegetation has been replaced by savannah grasses from Africa, a practice that has occurred for at least two decades (Smith *et al.* 1998). According to Jiménez (1998), the introduction of grasses in the savannah zone influences the structure and function of the earthworm community but not the species richness.

Earthworms produce biogenic structures that are important for certain pedological processes (Decaëns *et al.* 2001a), hence the interest in measuring structures in a savannah soil and comparing those with another soil under introduced pasture usage. Jiménez and Decaëns (2004) have shown that *Martiodrilus n.* sp., a species endemic to the savannah of Carimagua (Colombia), has adapted successfully to pasture, significantly increasing its abundance. These authors argued that this species has different coping strategies because it originated in a soil with limiting factors, such as a low nutrient content, a high degree of compaction and drought periods. Decaëns *et al.* (2002) have studied the impact of land use change in a native savannah, where pastures and agriculture were introduced, by analysing earthworm biostructures and soil structure and found similar results in the soil structure between the pasture and savannah areas, whereas the agricultural soil showed signs of further deterioration. Thus, biostructure diversity decreases with the pasture and agricultural land usage, as compared to the savannah. The authors concluded that the change in land use to agriculture in the tropics involves risks with regard to the physical properties of the soil and earthworm communities.

Earthworm research in Mexico

The region of Southeast Mexico has suffered a heavy deforestation of areas of rainforest in order to promote extensive grazing land for livestock (Díaz-Gallegos *et al.* 2010). The pioneering studies of Fragoso and Lavelle (1992), which included 12 sampling sites on four continents, have shown that, by biomass, earthworms in the humid tropics represent the main group of macrofauna in the soil. Another study has shown that the diversity of earthworms is affected when natural systems are altered by human actions: native species are restricted to riparian habitats, and exotic species are found in transformed ecosystems (Fragoso *et al.* 1997). In contrast, pastures have been shown to contain both native and exotic species (Fragoso *et al.* 1997). In the case of tropical orchard systems, epigeic species such as *Amynthas gracilis* have been found, whereas in cropping systems, no conditions exist for epigeic habitats (i.e., areas characterised by an abundant litter layer). However, when ploughing is not part of the management system, some stenotopic species were able to survive in these ecosystems (*Ramiellona strigosa* and *Zapatadrilus* sp.). Similarly, it has been reported that under low-input agriculture and little or no movement of the soil, native species were maintained in the plots; in contrast, the combination of ploughing and the use of pesticides has resulted in the dominance of exotic species (Fragoso *et al.* 1997).

Huerta *et al.* (2007) have studied the diversity of earthworms in the state of Tabasco (Mexico), which has been heavily deforested. The sampling sites included the tropical rain forest and plantations of cacao (*Cacao theobroma*) and mango (*Mangifera indica*). The authors found 19 species (14 native and 5 exotic) belonging to the families Megascolecidae, Glossoscolecidae and Ocnerodrilidae. The sites with greater diversity were those in the tropical forest (9 species), which had a high soil organic matter (SOM) content. The cacao plots also showed a high diversity of species (13 species), whereas the highest biomass of earthworms was found in the mango plantations. The highest density of earthworm individuals was found in the riparian vegetation zone; however, the managed systems with intensive mechanisation, such as sugar cane and maize crops, had only one or two species of earthworms.

A study carried out in Central Mexico reported the results about the effects of four different types of tillage on the population of *Aporrectodea caliginosa* (an exotic species native to Europe) in maize monoculture plots, where crop residues were incorporated at relatively high rates (> 2.5 t ha^{-1} y^{-1}) for five consecutive years (Rosas-Medina *et al.* 2010). However, major differences were not found in this study with regard to the number of individuals (adults and juveniles) in plots worked by deep ploughing (disk or ripper) or shallow tillage (disking), confirming the adaptation of *A. caliginosa* to the mechanical operations of tillage equipment, as has been previously reported under a temperate climate (Ivask *et al.* 2007; Peigné *et al.* 2009).

Agroecosystem management and the effects on earthworm populations

The activities and populations of earthworms are intimately linked to the type of applied agricultural practices, such as the type of tillage, residue management, crop rotation, fertiliser types and overall management. Furthermore, the magnitude of the effect, whether positive or negative, also depends on the interactions with the soil type and water content, as is discussed in the following sections.

1. Effect of tillage operations on earthworm populations

Chan (2001) has reviewed the influence of tillage on earthworm parameters in different agro-ecosystems and has reported a controversial trend for the results. Some authors argue that tillage in arable soils reduces the number of earthworms due to the disturbance and loss of the physical quality of the soil, as compared to permanent pasture or reduced tillage, whereas other researchers have demonstrated that the earthworm population is maintained or increased after tillage operations. Experiments of long duration for the purpose of analysing the population dynamics have shown that earthworms under conservation agriculture tend to increase both in activity and the number of individuals when compared to conventional agriculture (Peigné *et al.* 2009). These types of studies have also shown that soil inversion particularly affects the anecic species (Holland 2004) due to the fact that these species move within the soil profile, whereas epigeic species inhabit the litter layer on the soil surface (Kladivko 2001).

The damages of the earthworms under tillage operations depend on the frequency and depth of the tillage and the restitution of crop residues to the soil. Tillage causes physical damage by exposing the worms to predators and habitat destruction (Clapperton *et al.* 1997; Chan 2001). Chan (2001) concluded that different species of earthworms are affected by tillage in different ways. It is possible to increase the number of worms after working a grassland soil due to the availability of organic material as food for earthworms.

Most studies on tillage and earthworm populations have been developed in temperate zones (Hendrix and Edwards 2004). Pommeresche and Løes (2009) have recently reported major findings about the ecology of earthworms in arable soils in Norway, where the main species present were *Aporrectodea caliginosa* and *A. rosae*, both geophagus worms. The former is known to tolerate the changes induced by agricultural mechanisation (Ivask *et al.* 2007; Peigné *et al.* 2009). *Lumbricus terrestris* is sensitive to mechanisation, though it does not completely disappear in soils that are ploughed yearly under conventional tillage. Pommeresche and Løes (2009) have reported that the density of earthworms in the soils of Norway varied between 30 and 350 m^{-2} individuals, with the lowest values corresponding to those soils under conventional tillage systems. When fallow periods are introduced in crop rotation, a recovery of earthworm populations and biomass occurs, as well as an increase in the number of earthworm galleries. For geophagus species, the Norwegian study indicated that the application of manure or green manure for short periods had a positive effect on the earthworm population. However, in general, these same species showed higher earthworm populations under shallow tillage (a depth of 15 cm); even at depths of 25 cm, ploughing was not a factor that prevented the growth of populations of earthworms. These results are consistent with those obtained in Central Mexico concerning the effect of different types of tillage on earthworm populations (Rosas-Medina *et al.* 2010).

According to Pommeresche and Løes (2009), a population of 350 individuals per m^2 corresponds to a passage of more than 200 tons of soil through the digestive tracts of geophagus earthworms, resulting in an increase in the macronutrients (present in the casts) available for crop nutrition. These authors have also reported an increase of 28% N, 36-53% of available P, and 40-59% of assimilable K in the casts, as compared to the nutritional content of soil in management systems under ley farming or animal manure application.

In the case of temperate regions, Pommeresche and Løes (2009) have reported that epigeic and composting species in Scandinavia were heavily pigmented and included *L. rubellus*, *Lumbricus castaneus*, and *Dendrodillus rubidus* and the composting species, *Eisenia fetida* and *Eisenia andrei*. The represented anecic species, which build permanent vertical galleries, were *Lumbricus terrestris* and *Aporrectodea longa* (Pommeresche and Løes 2009). Representatives of the group of endogeic species, which construct temporary galleries and leave their casts in the soil rather than on the surface, were *A. caliginosa*, *A. rosea*, and *Octolaseum cyaneum*.

It is important to increase the studies in both the wet and dry tropical regions of Latin America. Studies in Brazil have shown that no-tillage with residue retention is a system that contributes to the quality of the soil in tropical and subtropical areas (Aquino *et al.* 2008). In addition, a study was conducted in humid tropical conditions (1600 mm of rainfall $year^{-1}$; Brown *et al.* 2003) under Alfisols and Oxisols in Brazil that involved three types of tillage, conventional (CT), minimum (MT) and zero (NT), and included soil situations of both grassland and forest. The NT and MT plots have been managed in those ways for approximately 30 years and represent an experimental reference for the region. The sample was divided into two seasons: winter and summer. In winter, the highest density of earthworms was found in the grassland and the lowest under CT; however, in summer, the highest recorded number of earthworms was found in soils under NT and MT and the lowest under CT. The authors also noted a correlation between the number of worms and the C content, which increased in the first 10 cm of the soil profile under conservation agriculture, in which crop residues are left on the surface without ploughing.

Capowiez *et al.* (2009) have emphasised that several studies have addressed the issue of the influence of tillage on earthworm individuals; however, these authors proposed more detailed studies on the type of earthworms that are found in each type of agricultural system because each earthworm type performs different functions (**Table 1**). The authors argued that the greatest amount of research has been focused on anecic species, which are not dominant in arable soils (Lee 1985). Capowiez *et al.* (2009) argued that the effects of CT, as compared to NT, are not necessarily a decrease in the abundance of earthworms but a change in the structure of the earthworm community. These authors found a decrease in anecic earthworms due to the effects of tillage, which was linked to the break of biopores in the structure of the arable profile, resulting in areas of high soil compaction. Indeed, different species have different levels of tolerance to soil compaction. The authors further showed that the type of tillage did not affect a particular class of endogeic worm (*A. rosea*), whereas the population of another class (*A. caliginosa*) increased significantly in plots under tillage. In a recent study in Mexico that involved maize monoculture plots for 5 consecutive years (Rosas-Medina *et al.* 2010), no differences were found among deep and shallow tillage in relation to the number of individuals of *A. caliginosa*, which was consistent with the tolerance to tillage operations attributed to this species (Ivask *et al.* 2007; Peigné *et al.* 2009).

Table 1 Earthworm types and theirs habitats. Modified from Chan (2001) and Barois *et al.* (1999).

Category	Subcategory	Description
Epigeic	Epegic Epi-anenic Epi-endogeic	Species that live above the mineral soil surface, typically in the litter layers. Typically, they have relatively high reproductive rates and grow rapidly.
Anecic	Anecic	Species that live in burrows in mineral soil layers but come to the surface to feed on dead leaves which they drag into their burrows; some make burrows that extend deep into the subsoil.
Endogeic	Polyhumic Mesohumic Endo-anecic Oligohumic	Species that inhabit mineral soil horizons, feeding on soil more or less enriched with organic matter.

It is important to determine the function of each species in order to correctly interpret the decrease or increase in their populations and biomass. For example, Peigné *et al.* (2009) have argued that increases in the population of anecic earthworms in a no-till system positively affects the soil structure, and a comparison with a tilled soil revealed a lower number of earthworms with more compacted soil.

Bottinelli *et al.* (2010) have conducted a study in the soils of temperate regions, with the goal of determining the interaction of earthworms with the soil structure (aggregate stability) in soils subjected to different types of tillage (i.e., mouldboard ploughing, surface tillage and no-tillage). The researchers measured the abundance and water-stable casts located in the soil profile and found that, in NT soils at depths of 2 and 12 cm, there was an increase in the number of casts, as compared to other tillage systems. The interpretation was that the number of endogeic and anecic earthworms was high under NT because, in the absence of tilling operations, the casts are not destroyed, and the high soil bulk density further prevents the degradation of the casts by the erosive effects of the soil water. The authors also found that in all of the treatments, more casts were found at a depth of 12 cm compared to 2 cm, deducing that the deeper the soil was, the higher was the stability of the casts. Furthermore, casts at depths less than 2 cm were not involved in the stability of soil aggregates.

This review has described the influence of non-tillage techniques on earthworm populations, but little information is available about the impact of the excessive use of agrochemicals on earthworm populations in non-tillage plots. In a study conducted in Cordoba, Argentina, Domínguez *et al.* (2010) evaluated the influence of non-tillage techniques on some physical properties of the soil and on the macrofauna and the decomposition of litter. Natural grassland was used as a control. Fewer earthworms were found in the non-tillage plots than in the grassland. The difference resulted from the heavy use of toxic agrochemicals in the non-tillage plots. The authors concluded that the non-tillage regime used in the study area would endanger the maintenance of ecosystem functions. Aquino *et al*. (2008) assessed the abundance and richness of macrofauna, including earthworms, in non-tillage systems with different types of plant cover in the Cerrado, Brazil. The results of this study were consistent with the conclusion reached by Dominguez *et al*. (2010) that non-tillage techniques impact macrofauna negatively compared with natural systems.

2. Effect of crop residue management and the quality of organic substrates on earthworm population parameters

Some of the negative effects of tillage on earthworms can be reduced in soils by retaining crop residues. The input of organic material and crop diversification provides both biotic and abiotic conditions that are favourable for earthworm populations and an increase of the organic substrate (Osler *et al.* 2008). However, the response of earthworm populations also depends on the characteristics of the crop residue retained, specifically the C: N ratio. In a study conducted in Canada, no significant differences were found in earthworm populations subjected to the incorporation of different crop residues (i.e., barley, wheat, clover, soybean and canola). The proposed explanation was that, for 15 years, these plots were planted with corn thus, the crop residue had a C: N > 60 and involved slow decomposition rates, which, in turn, provided available food for the earthworms (Eriksen-Hamel *et al.* 2009).

The quality of the organic matter is a factor that affects both the population and the biomass of earthworms. Leroy *et al.* (2008) have compared the effects of manure and slurry from two types of compost on the earthworm population and found that materials with high contents of polysaccharides and proteinaceous substances (manure and slurry) had a promoting effect on the number and biomass of earthworms.

In a laboratory microcosm experiment, García and Fragoso (2003) studied the effect of different plant substrates on the reproduction of *P. corethrurus* (an endogeic species) and *Aminthas corticis* (an epigeic species). The organic substrates of different food quality tested were as follows: (a) high quality, fresh leaves of mucuna (*Mucuna pruriens*) and cacahuatillo (*Araquis pintoi*), (b) medium quality, litter of macadamia (*Macadamia tetraphyla*) and (c) low quality, sawdust (*Pinus patula*). The above were included in six different substrate mixtures with mineral soil as the basic substrate. The weight of the individuals and the cocoon production of each species were recorded every 12 days. A maximal weight was observed for *P. corenthrurus* in the mixture of soil-mucuna-sawdust, whereas minimal weights were obtained in all of the cacahuatillo mixtures. The authors concluded that, for growing populations of either species, mixtures of substrates of both high and low quality are needed. This strategy of combining organic substrates of different quality seems to be suitable for both vermicomposting systems and earthworm populations in agroecosystems (Hendrix and Edwards 2004).

3. Organic matter mineralisation and its physical protection by the actions of earthworms

The role of earthworms in the stabilisation or degradation of organic matter in soil has been analysed from various perspectives. Some authors have concluded that earthworms influence organic matter decomposition because they directly consume it (Springuett Syers 1984; Kotcon 2011) or because they accelerate the mineralisation of the C content in the complex organic polymers of the soil (Anderson 1989). Other researchers have argued that the activity of earthworms, especially endogeic species, promotes the conservation of organic C in the casts by a physical protection of the undigested organic matter. In general, earthworms have both internal (ingestion and changes associated with the digestive tract) and external (defecation and mobility) mechanisms that determine their dynamic effect on the soil organic matter (Wolters 2000).

Research has also been conducted on the decomposing action of earthworms. For example, in an experiment lasting 420 days in tropical soils inoculated with earthworms, the C mineralisation rates were 3.3 times higher in the uninoculated soil (Anderson 1989). In an experiment in New Zealand that included different horticultural crops with the addition of earthworms, there were observed increases in microbial activity, resulting in a greater decomposition of the organic matter because the faeces of the earthworms had a high microbial load, which, in turn, boosted the activity of soil microorganisms (Springett *et al.* 1992). High rates of mineralisation can become an undesirable effect of agriculture in relation to carbon capture and CO_2 emissions. It is, therefore, necessary to study the emissions produced by earthworm populations in detail and relate the results to the quality of organic substrates. In general, organic matter with a low C: N ratio decomposes rapidly, regardless of whether earthworms are present, and the inclusion of substrates of high C: N ratios may be beneficial due to the longer time required for the decay of the OM by the population of earthworms (Edwards and Hendrix 2004).

Earthworms can help to reorganise the distribution of C according to the size of the soil particles that are associated with the organic matter. Using the physical separation of organo-clay and organo-silt complexes and coarse plant residues (< 2, 2-20 and > 20 µm, respectively), Gilot *et al.* (1996) have evaluated the effect of earthworm inoculation on the distribution of C in different soil granulometric fractions. The presence of earthworms induced a rapid decrease of C concentrations in coarse fractions, with a corresponding increase in the proportion of the C content in fine soil fractions.

Other laboratory experiments have shown that earthworms stabilise the organic matter within aggregates that are formed by their activity; however, the reported effects vary depending on the ecology of the earthworm species, the nature of their depositions and the structures created by their activity (Gilot *et al.* 1996). In field experiments (3 to 7 years) using plots of low-input corn grown for two years in the Ivory Coast, Peru and Mexico, no conclusive results were obtained to verify the hypothesis that earthworms help to preserve the C and nutrients in the soil (Gilot *et al.* 1996). In the Ivory Coast, where six annual, continuous maize cycles were tested, the first three years of experimentation revealed that the inoculation of earthworms resulted in an increase of the incorporation of C derived from the maize residues. Such increases ranged from 2.9 to 6.9% compared to the non-inoculation treatment. However, measurements at the seventh cycle showed that the contents of soil-stored C decreased from 1.62 kg m^{-2} to 1.13 kg m^{-2} in inoculated plots, whereas in plots without earthworms, the soil C content was 1.24 kg m^{-2}, and there were no statistical differences. In a study in Peru, earthworm inoculation reduced the soil C loss only in years 2 and 3, but, in the sixth year of cultivation, there was a reduction of the total soil C, indicating that additional years of earthworm inoculation are needed to reach a balance in the C content. Furthermore, it is assumed that the type of inoculated species plays an important role. In the Ivory Coast study, the species *Millsonia anomala* demonstrated cumulative effects, whereas *P. corethrurus* stimulated carbon mineralisation (Gilot *et al.* 1996).

4. Crop rotation and its effect on earthworm populations

Crop rotation or the use of cover crops is another factor that determines the density of earthworms. In Mexico, the legume *M. pruriens* has been used as a cover crop to strengthen the growth and yield of maize (Chikoye and Ekeleme 2003; Eilitta *et al.* 2003). Ortíz-Ceballos and Fragoso (2004) have detected a higher population of the native endogeic earthworm *Balanteodrilus pearsi* in a maize field with *M. pruriens*, as compared with a maize monoculture. Some authors have demonstrated the importance of earthworms in tropical cropping systems of certain plants, such as maize (Pashanasi *et al.* 1996; Brown *et al.* 2004). Ortiz-Ceballos *et al.* (2005) have shown that increasing the N content in the soil with the use of a cover crop or green manure resulted in increases in the growth and reproduction of *B. pearsi*. Similarly, Ortiz-Ceballos *et al.* (2007) later showed that the presence of *M. pruriens* residues not only benefited the development of maize crops but was also correlated with the growth and reproduction of *B. pearsi*. This was attributed to the increased addition of N (2.3%) coming from the *M. pruriens* depositions, which are easily mineralised and, subsequently, provided more N to the plant. This contradicts the idea that endogeic species contribute very little or nothing to the decomposition of litter (Chan 2001; Lavelle and Spain 2001). The study by Ortiz-Ceballos *et al.* (2007) showed a synergistic process between *M. pruriens* and *B. pearsi* that caused a release of nutrients that promoted the development of the root system and increased the biomass of the maize grain. According to Edwards and Hendrix (2004), this area of study requires further research in both temperate and tropical zones.

In Latin America, the traditional system of livestock production has had negative effects on soil quality, including biological diversity. This problem has prompted a search for new alternatives that combine different crop and tree species to create silvopastoral systems. In Cuba, Sánchez and Crespo (2004) investigated earthworm biomass and density in soils managed under two systems, a grass monoculture and a mixture of grass and leguminous trees (*Leucaena*). The results of their study showed that the biomass of earthworms was higher in the silvopastoral system than in the grass monoculture (57 and 27% of the total macrofauna, respectively).

Zerbino (2010) evaluated the soil macrofauna, including earthworms, in an agricultural experiment in Colonia, Uruguay. The experiment involved different crops, pasture, and continuous cropping with and without fertilisation. The following rotations were used (percentage refers to time): (a) 33% agriculture and 66% pasture; (b) 50% agriculture and 50% pasture; and (c) 66% agriculture and 33% pasture. The rotation that used 33% agriculture and 66% pasture with a crop of legumes had the highest population densities of macrofauna, including earthworms. The author assumed that the crop rotation system produced changes in the structure and density of the vegetation. The rotation with the highest levels of organic C and total N in the soil favoured habitats and nutrient resources that would be available to earthworms. The study concluded that earthworms are an indicator of soil degradation.

5. Earthworms under organic agriculture

One of the primary goals of organic farming is the preservation of soil fertility using agricultural techniques, such as conservation agriculture (Franzluebbers 2002) and a reduction of agricultural chemicals, which has been reported to create a favourable habitat for earthworms (Pfiffner and Mäder 1998). Paigné *et al.* (2009) have measured the population of earthworms at three sites under organic farming practices using conventional tillage, no-tillage and crop rotation plots in the short term. The authors concluded that tillage reduced the biomass and abundance of earthworms in agricultural crop rotations with grass, a trend opposite to that reported by Brown *et al.* (2003), who showed that, in areas of Brazil, earthworm populations were higher in pastures. Once again, it is clear that the trends in earthworm population dynamics are affected by both climatic and soil conditions in the area of study. Thus, generalised cause-and-effect relationships cannot be made for all regions of the world. The results of Paigné *et al.* (2009) demonstrated that organic production that focused mainly on growing vegetables favoured earthworms, and the agricultural system that largely preserved the earthworm community was the no-tillage and cover-crop systems.

Several new systems have been implemented in Norway. A promising innovation was the inclusion of clover and pasture in cropping rotation systems, as opposed to merely the cultivation of crops using chemical fertilisers. The results that followed showed that, in crop rotations under ploughed soil, the biomass and density of earthworms were lower compared to pasture rotation and the incorporation of manure. Similarly, it has been shown that the application of chemical fertilisers did not sustain the population of earthworms, which was maintained at normal levels with the incorporation of manure (Pommeresche and Løes 2009).

Metzke *et al.* (2007) have studied the effect of tillage depth (10 and 30 cm deep) on the earthworm population in plots under organic agriculture for 12 years, concluding that a reduction in tillage depth did not contribute to an improvement in the habitat of the earthworms. Similarly, in a study in Central Mexico, it was found that neither conventional (25 cm) nor shallow (15 cm) tillage affected the earthworm population density or the galleries in the topsoil (Rosas-Medina *et al.* 2010).

Organic amendments have been used by producers to counteract the low productivity found for agroforestry systems in the Venezuelan savanna. A study was conducted to evaluate the earthworm communities in a natural savanna and an organic farming system (Araujo and López-Hernández 1999). In the savanna, the earthworm density and total biomass were 35.2 individuals m^{-2} and 1.1 g m^{-2}, respectively, whereas the density and biomass under organic agriculture were 155.2 individuals m^{-2} and 18.6 g m^{-2}, respectively. The authors argued that the organic amendments improved the soil characteristics compared with the savanna soil and that these improvements produced an increase in the earthworm population. However, the diversity of earthworms was lower in the organic plots than in the savanna. The authors hypothesised that the incorporation of organic amendments induced changes in the soil microclimate as well in the natural food of earthworms. These changes could cause the disappearance of some earthworm species and favour those species having a greater ability to adapt to new conditions.

In Paraná (Brazil), Bartz *et al.* (2009) conducted a comparative study of earthworms in conventional and organic coffee fields and in a native forest. In both winter and summer, the plots under organic management showed higher earthworm density, biomass and species numbers compared with the other systems. However, plots under coffee, both with organic and conventional management, had peregrine or exotic species, whereas the forest only had native species.

6. Soil water content and soil texture in relation to earthworm populations

Working in Central Mexico, the authors of this review have observed normal or large populations of earthworms in soils with clay-loam texture characterised by a relatively high clay content (close to 300 g kg^{-1}; Fuentes *et al.* 2009; Rosas-Medina *et al.* 2010). Observations of arable soil in a micro-region dominated by volcanic sandy soils (790 g kg^{-1}) over a period of five months without rain (De León-González 2006) indicated the absence of individual earthworms for at least 10 years of the field observations, which is consistent with reports of the absence of earthworms in dry areas of Northern Mexico (Fragoso 2001). Therefore, the soil moisture appears to be a variable that governs earthworm populations, as has been noted previously (Chan 2001; Edwards and Hendrix 2004). In a study conducted in a clay-loam soil with 300 g kg^{-1} clay in Central Mexico under an irrigated system, it was found that the main factor that determined the changes in earthworm populations was the time of year rather than the intensity of mechanical tillage operations. At the time of planting of the maize monoculture, the soil water content was low, and adult and juvenile individuals of *A. caliginosa* were absent in the soil profile. In contrast, when samples taken before and after

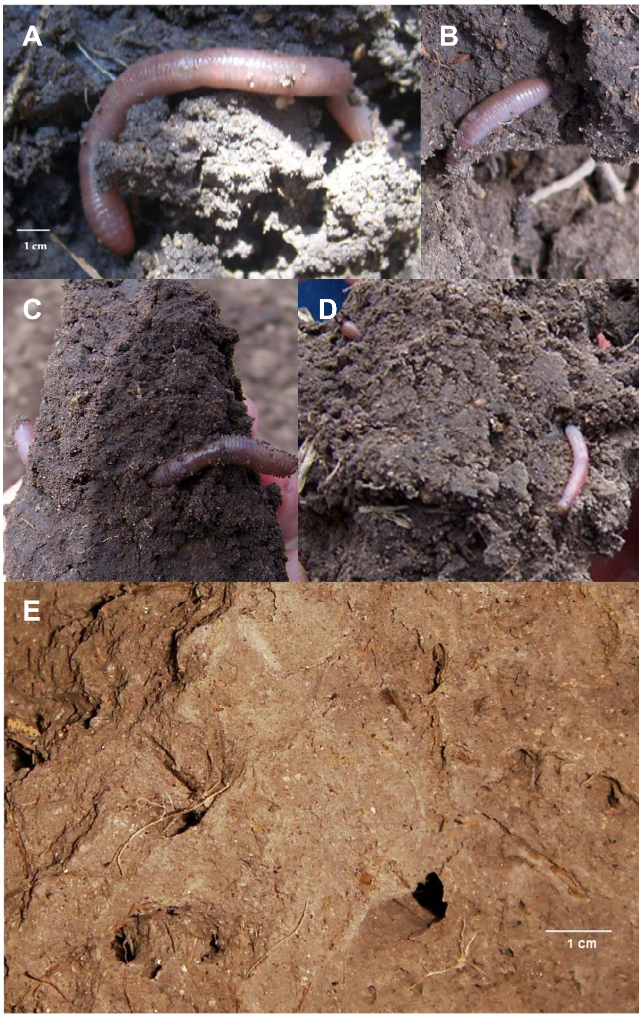

Fig. 1 Individuals of *Aporrectodea caliginosa*, an exotic earthworm species well adapted to a clay-loam soil under maize monoculture (irrigated fields at Toluca, central Mexico). The activity of earthworms of this species leads to an extensive network of galleries which contribute to the structure of arable soils (Rosas-Medina *et al.* 2010). Photo (**A**) by Miguel Ángel Rosas-Medina, and (**B−E**), by Mariela Fuentes-Ponce. Adult living in a soil profile with abundant crop residues. Adult creating galleries in the soil profile. Individual clod colonized by an adult. Individual clod colonized by a juvenile earthworm. Empty earthworm burrows on the surface of a dried and hardened clod.

harvest, during which the soil moisture was higher than at planting time, a strong recovery of earthworm populations was observed, reaching up to 135 individuals m^{-2} (Rosas-Medina *et al.* 2010).

Rosas-Medina *et al.* (2010) have compared the effect of four types of conventional tillage, using different combinations of the type of plough (disk or ripper) and disk harrow. The results indicated that, regardless of the intensity and depth of tillage, the number of galleries made by *A. caliginosa* remained statistically unchanged, reaching very high values (> 2500 burrows m^{-2}; **Fig. 1**). To explain these results, the authors hypothesised the following: the high clay content (300 g kg^{-1}) was favourable for earthworm population, as indicated by studies in temperate regions (Chan 2001), and the cutting action of tillage tools did not entirely eliminate the galleries created by the worms. Thus, for clay-loam soils, the clay content makes soil highly massive when dry, and earthworm galleries are retained, at least partially, after tillage operations.

The high number of earthworm burrows found in the study by Rosas-Medina (2010) in a clay-loam soil under conventional tillage may be an additional reason to analyse the contribution of earthworms to a soil structure (Edwards and Hendrix 2004). Indeed, the interactions between the soil-cementing capacity (as determined by the content of expandable clay) and the structure of burrows and other pores created by earthworms seem to be crucial in relation to the permanence of these structures. There is evidence that when the soil mechanical behaviour produces soil massive structures, the burrows created by earthworms can exist for several years, provided that the earthworms are still reproducing in the soil. It would be interesting to analyse the distribution of nutrients associated with the galleries located at different depths of soil for different tillage treatments.

The study of Rosas-Medina *et al.* (2010) has indicated that irrigation plays a positive role in the development of earthworm populations in areas with long periods of drought. A greater number of studies is required for Mexico and Latin America for the analysis of the dynamics of earthworm populations in arable soils or pastures that receive irrigation, which occur, in particular, in the flat lands of Northwest Mexico (the area of the highest agricultural productivity in the country), and other areas that benefit from irrigation in the central and northern regions of the country. These studies should integrate the issues of the persistence of pesticides and heavy metals in the soil as factors that alter earthworm populations in arable soils.

Regarding soil texture, Gerard and Hay (1979) have compared earthworm populations in a clayey soil and a sandy soil in England and reported a 40% increase in the number of individual earthworms in the clayey, as compared to the sandy clay soil. It is possible that the effect of texture is also related to the greater ability of the clay to form aggregates that protect the organic matter (the food of geophagus species), demonstrating another crucial factor for the development and maintenance of populations of earthworms in arable soils. The fine texture and organic matter associated with soil particles seem to play a role reducing of chemical changes produced by the application of fertiliser materials. It has been reported that applications of liquid manure (Curry 2004) or inorganic fertilisers based on ammonia caused damage to earthworms in the short term, especially those in sandy soils (Lofs-Holmin 1982).

In a study focusing on the diversity of earthworm species in the Mexican rainy tropics (Tabasco), Huerta *et al.* (2007) found a strong correlation between the number of individuals and the clay content of the soil. In another region of Mexico (Veracruz), Huerta (2002) identified a negative relationship between the sand content and the abundance of *Polypheretima elongata* in a pasture area (Huerta 2002).

7. Earthworms populations as soil quality indicator

Earthworms are inherent soil inhabitants and, thus, play a key role in the ecosystem, both in the degradation of organic matter and the structure of the ecosystem (Römbke *et al.* 2005). These organisms depend primarily on soil characteristics and climate, in comparison to other ecosystem conditions (e.g., the presence of predators). The close relationship between the soil conditions and the life of the earthworms is the basis for considering the density and population dynamics of earthworms as an indicator of soil quality. For several years, earthworms have been used as indicators of forest soil quality, linking the species with particular soil properties (Römbke *et al.* 2005). However, the dynamics of earthworm communities are also affected by human actions in agroecosystems (Decaëns *et al.* 2001b). Their response has been particularly correlated with changes in plant cover, which determine the amount and quality of the soil organic matter (Decaëns *et al.* 2001b). It is known that the content and quality of soil organic matter (SOM) is an indicator of the soil quality (Karlen *et al.* 2006); therefore, if the earthworms are closely related to the dynamics of the SOM, the density and distribution of earthworms could be considered as an indicator of the soil quality, particularly in agricultural lands. Earthworms are sensitive to disturbances related to agricultural practices and the intensity of land use, is more evident in systems that increase the soil C (Ayuke *et al.*

2011).

Earthworms are especially sensitive to chemical changes in the ecosystem; therefore, they are reliable indicators of soil quality in agroecosystems subjected to the application of herbicides, fertilisers and pesticides, as well as soil contaminants (e.g., heavy metals) (Hund-Rinke and Wiechering 2001). Studies conducted in Europe have analysed the association of soil properties, such as the pH, texture, C: N ratio, organic C and water content, with the density and biomass of different groups of earthworms (Graefe and Beylich 2003). Römbke *et al.* (2005) have concluded that the soil water content was the soil property that was most highly correlated with earthworm populations, in comparison with other soil properties. Moreover, the water content is closely linked with the texture and amount of the SOM. The authors also found a correlation between the soil density and species, depending on the type of land use, concluding that some species of Europe are indicative of site-specific conditions (Römbke *et al.* 2005). However, the dynamic in the tropics is different than that in Europe, as will be discussed below. In addition, the structure and abundance of earthworm communities are also indicators of biodiversity and soil biological activity (Lavelle 1997; Mathieu *et al.* 2005; Pulleman *et al.* 2005).

The most noticeable changes related to specific types of farming are found in the topsoil, at depths up to 25 cm, where there is less mechanical disturbance by tillage. Earthworms are a better indicator of the influence of long-term agricultural managements with regard to the earthworm populations found in the topsoil (Pommeresche and Løes 2009). As mentioned above (**Table 1**), earthworm communities occupy a specific place in the soil profile according to their ecological characteristics (epigeic, anecic or endogeic), which is a potential biological measurement of the quality of temperate soils, but not in tropical areas, where the niches of different types of earthworms are not strictly defined (Römbke *et al.* 2005). Lavelle (1988) has proposed the creation of earthworm subgroups that are consistent with food preferences within each group, which would help in the tropics to build biological indicators of soil quality.

Velásquez *et al.* (2007) has assessed the quality of soils in Nicaragua and Colombia, including soils under different crops (e.g., coffee, maize and pasture), forest soils and eroded soils, using the sub-indicators of soil aggregation, organic matter content, and the morphology and biodiversity of the macrofauna, especially earthworms, which are particularly sensitive to disturbances in the ecosystem. The abundance and diversity of invertebrates in the soils of Latin America can be a potential indicator of the different aspects of soil quality (Ruíz-Camacho 2004). It must be emphasised that soil quality indicators should be generated according to the agroecological conditions of the studied area. However, several studies in different parts of the world have shown that the earthworm population is a potential tool in this regard, but we must be clear with respect to the particular parameter(s) to be measured around the dynamics of these organisms.

Importantly, earthworms interact with other soil organisms, plants and roots, forming systems that regulate the flow of the ecosystem or agricultural system, and this organisation will give some degree of resilience to the system. However, when there are improper practices and limits are exceeded, the resilience of the system and the earthworm communities will be affected, thus acting as an indicator of soil deterioration (Lavelle *et al.* 2006).

Earthworms can also be an indicator of the degradation or rehabilitation of the environment, and the presence or absence of certain species will determine the guidelines. For example, in some cases, endogeic species are more tolerant to pesticides and heavy metal residues, in comparison with some anecic species with deeper habitats (Paoletti 1999).

This section argues that earthworms can serve as indicators of soil quality. However, it is necessary to work with the producers to communicate the importance of the earthworm macrofauna for the quality and health of the soil. A study conducted in Camaquã, Rio Grande do Sul, Brazil (Rodrigues and Brussaard 2010) investigated the perspectives of farmers on different indicators of soil quality. Most of the respondents replied that earthworms can indicate soil quality. However, it was also found that the producers do not have the information that they need to relate their observations of the soil to the effects of soil properties on earthworm communities.

The use of earthworms as bioindicators in relation to environmental issues is emerging in Latin America. The 3rd Latin American Meeting on Oligochaeta Ecology and Taxonomy, held in Curitiba in December 2007, discussed this topic. Brown and Domínguez (2010) reviewed the functional characteristics of the earthworms that might serve as indicators. Their review considered the role of earthworms as agents of environmental change and stability. The authors argued that earthworms can serve as indicators of environmental quality, of environmental processes and of the nature and complexity of different habitats. They indicated that data on earthworms can be used to evaluate the productive potential and biodiversity of the soil, environmental quality, environmental disruption, and the performance of ecosystem management. Thus, the presence, abundance and diversity of earthworms may serve as tools to assess the impact of different human activities on different systems. The authors also emphasised the need in Latin America to conduct joint investigations on the taxonomy and ecology of different earthworm species in the region, most of which are endemic.

Exotic earthworms have been identified as indicators of disturbance. Fernandes *et al.* (2010) evaluated the effect of human disturbance on the incidence of exotic and native earthworms in the soil in a tract of Atlantic forest in São Paulo, Brazil. The earthworms were sampled in an area where the vegetation was completely cut and burned. Samples were also collected in another area where only selective cutting occurred. In all, 91.4% of the earthworm individuals collected was found in the area where there was complete cutting and burning. A more important finding was that all individuals in the area without vegetation belonged to an exotic species (*Amynthas* sp., *A. gracilis*, *A. corticis*) or a peregrine species (*P. corethrurus*). The authors concluded that human disturbance affects the surface activity and abundance of exotic earthworms and that the earthworms can be used as biological indicators of anthropogenic disturbance.

Human activities have introduced foreign substances (agrochemicals) into the environment. As a result, the soil is now physically and chemically degraded. It is necessary to repair the resulting ecological imbalances. For this reason, it is important to obtain indicators for environmental monitoring. Earthworms have emerged as one of the more important indicators for soils. Because of their ecological niche and lower position in the food chain, earthworms are bioindicators of the ecotoxicity of chemicals arriving in and accumulating in soils. They serve to indicate the presence of bioaccumulation in the food chain (Castellanos and Hernández 2007; Nahmani 2007). Andréa (2010) developed the use of earthworms in Latin America as environmental bioindicators for this purpose. Thus, earthworms are used to measure the degree of toxicity and bioaccumulation of pesticides. The species *Eisenia fetida* (Savigny, 1826) and *E. andrei* (Bouché, 1972) are internationally accepted as bioindicators of harmful effects of heavy metals, petroleum derivatives and antibiotics. The responses of the worms are unique to each species, and bio-alterations can be seen in the eggs, galleries and the behaviour of the earthworms.

8. Earthworms and greenhouse effect gases

Earthworms can affect the structure and diversity of the microbial community; therefore, they are believed to be an important factor in the emission of greenhouse gases (Luo *et al.* 2008). One of the interactions between the earthworms and soil microbiota is that the structures generated by the earthworms provide a habitat for microbial communities (Marhan *et al.* 2007). These conditions stimulate the emission of CO_2 and N_2O (Caravaca *et al.* 2005; Bertora *et al.* 2007). However, it has also been shown that earthworms contribute to the C sequestration by stabilising the micro-organic matter in stable aggregates that are rich in C, which is within the macro-aggregates. Thus, it appears that earthworms contribute to reducing CO_2 emissions but increase the emission of N_2O (Bossuyt *et al.* 2005; Pulleman *et al.* 2005). A laboratory study has shown that the endogeic species of tropical soils (*P. corethrurus*) induced an increase in the CO_2 emissions but did not affect the N_2O fluxes. The authors attributed this to an increase in microbial respiration favoured by the conditions that encouraged earthworm reproduction (Chapuis-Lardy *et al.* 2010).

Many studies on greenhouse gases (GHGs) have focused on CO_2 because their emissions are higher compared to N_2O; however, the latter is 300 times more effective as a GHG than CO_2 and contributes to the stratospheric ozone depletion (Cavigelli and Robertson 2000). Approximately 62% of the global emissions of N_2O are emitted by soils of both natural and agricultural ecosystems (IPCC 2007).

It has been shown that the earthworm digestive process of denitrification involves the release of N_2O and N_2 (Drake and Horn 2006). Sheehan *et al.* (2006) have argued that the diversity of earthworms and their interactions with microbial communities are involved in the processes of mineralisation, nitrification and denitrification. Speratti and Whalen (2008) have conducted a study in which they measured the CO_2 emissions at the level of a laboratory microcosm and detected a positive correlation between the earthworm biomass and gas emissions. In addition, they reported that the mixture of anecic and endogeic species resulted in higher concentrations of emitted CO_2, as compared to a microcosm inhabited by a single species, concluding that microbial respiration was stimulated by the interaction between the two earthworm classes. Regarding the emissions of N_2O in the microcosm inhabited only by the anecic species, denitrification was the dominant process, with a concomitantly increasing gas emission, whereas in the endogeic-species microcosm, the main process was nitrification. Furthermore, the microcosm with mixed species experienced more denitrification (i.e., produced more N_2O) than nitrification.

Under wet conditions and in the presence of NO_3^-, the activity of anecic earthworms can create a preferential flow to increase water infiltration and nutrient leaching (Domínguez *et al.* 2004), and the presence of denitrifying bacteria stimulates the emission of N_2O (Horn *et al.* 2003; Costello and Lamberti 2008). Assuming that the denitrification process would be increased in wetlands, a study was conducted in Canada to determine whether more earthworms were present in the vegetated riparian buffer strips that were created to intercept nutrients and protect water quality near agricultural fields (maize). The conclusion was that the abundance of earthworms did not differ in the areas sampled nor did the N_2O emissions. However, at the laboratory microcosm level, the study showed that emissions could be potentially greater in riparian buffer strips than in agricultural lands (Bradley *et al.* 2011).

Giannopoulos *et al.* (2010) have compared the effect of incorporating the arable profile or leaving crop residues on the soil surface on the activity of earthworms and GHG emissions and found an effect of the species of earthworm. Before the incorporation of the crop residues, *A. caliginosa*, an anecic species, increased the N_2O emissions from 1350 to 2223 mg N_2O-N kg^{-1} soil; however, *L. rubellus*, an epigeic species, did not produce an increase in N_2O emissions. When residues were left on the soil surface, the presence of *A. caliginosa* showed no change in the emissions, whereas *L. rubellus* increased emissions from 524 to 929 mg N_2O-N kg^{-1} soil. Furthermore, the CO_2 emissions were only affected by the presence of *L. rubellus*. These results showed that both species of earthworms had the potential to increase emissions of N_2O while interacting with crop residues; however, the increase in emissions was greater when the residues were incorporated into the soil by conventional tillage than when they were left on the soil surface (zero tillage). The incorporation of residues by tillage promotes earthworm activity and affects the physical properties of the soil, such as the decrease or increase in bulk density, which influences the emission of N_2O (Ball *et al.* 1999; Van Groenigen *et al.* 2005). However, Rizhiya *et al.* (2007) have proffered a different opinion in this regard, stating that N_2O emissions are not dependent on soil bulk density. These same researchers reported a study under laboratory conditions and have suggested that emissions of N_2O could be reduced if crop residues had a relatively low C:N ratio, which could be achieved by leaving crop residues on the soil surface a few weeks before their incorporation by conventional tillage. In this regard, they recommended more field experimentation. Indeed, much of the work to date has been conducted under laboratory conditions; thus, there is still much to investigate about the relationships between earthworms and GHG emissions under field conditions in different agro-ecological conditions, particularly in Latin America, where climatic conditions differ from the temperate areas of Europe and North America.

CONCLUSIONS

Research on the ecological functions of earthworms in the arable soils of Latin America has many gaps that need to be resolved. Compared with the information generated in temperate countries, studies on earthworms in the agroecosystems of Latin America are still incipient. Future studies that focus on arable or grassland soils can benefit from the great progress made in Latin America by the international research networks formed by ecologists and taxonomists. These cooperative efforts have enabled the studies of earthworms in natural ecosystems in different parts of the region and of the world, allowing comparisons of the nature of communities of earthworms and their sensitivity to changes in land use (mainly from tropical forest to grassland or cultivated plots with species of fruit trees or annual crops, such as maize) and plots subjected to different types of agricultural management. This network is essential to increase the research in agroecosystems because the collaboration between ecologists and taxonomists with agronomists interested in the ecology of earthworms can generate relevant information for making decisions about agricultural management that are appropriate for response to soil and climate conditions in that particular region. In the case of Mexico, research on earthworms in agriculture has been concentrated in the central and southeast regions, where rainfall and temperatures are intermediate or high, and the organic substrates enable the development of earthworm populations in the soil. However, there is a great lack of information about earthworms in arid and temperate areas under irrigation and different management systems.

Based on the review presented here, some of the premises for research on the ecology of earthworms that are indicative of the region of study are as follows: (a) the presence or absence of native species in arable soils or pastures, in relation to the quality of the organic substrates available to the earthworms; (b) the effect of pesticides, herbicides and heavy metals on earthworm populations (toxicology); (c) the effect of soil moisture gradients on earthworm populations (both native and introduced) in both irrigated and rain-fed lands; (d) regional studies using earthworm populations as soil-quality indicators; (e) studies on food webs involving earthworms, fungi and bacteria in the soil and root systems of plants grown in different agroecosystems and (f) measurements of CO_2 and N_2O in different management systems and intensive vermicompost systems. As pointed out by Edwards and Hendrix (2004), using what has been achieved in Australian programs as a paradigm, it would be beneficial if the majority of the research conducted in agroecosystems combined both short- and long-term studies and involved farmers in the dissemination of knowledge of the earthworms and their effects on soil and crop development.

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